WINDSOR

Rethinking Comfort

Proceedings

Edited by
Dr Luisa Brotas
Prof Susan Roaf
Prof Fergus Nicol
Rev Prof Michael Humphreys

Proceedings of 10th Windsor Conference
Rethinking Comfort

Cumberland Lodge, Windsor, UK, 12th-15th April 2018
Windsor Conference 2018 www.windsorconference.com

ISBN 978-0-9928957-8-5
Published by NCEUB 2018

RETHINKING COMFORT

THE TENTH WINDSOR CONFERENCE

INTRODUCTION TO THE PROCEEDINGS

The history of past Windsor Conferences can be found on our website, http://windsorconference.com. But it can also be seen in the growth in size and cohesion of our thermal comfort community. The friendly ambience of the venue and the inclusive nature of its deliberations have helped to nurture a group of people who not only value each other's special gifts and enthusiasms but also use them to evolve their own thinking and develop new research directions. Windsor has always benefitted from the mix of delegates to the conference from the most experienced thinkers to those whose whole professional future is still ahead of them.

This volume includes all the papers presented at the tenth Windsor Conference which was held from April 12th to the 15th 2018 at the Cumberland Lodge Conference Centre in Windsor Great Park. The tenth conference was attended by 103 academics and building professionals from 24 countries. 77 papers were presented by their author or co-author and also in the proceedings are 11 papers by authors who for one reason or another were unable to attend. The structure of the conference had an emphasis on the seven themed sessions attended by all delegates. Each of these addressed a particular area of research, meaning that every delegate had the opportunity to contribute to, and learn about, the many different facets of the subject. Nine parallel workshops targeted more specialist issues of theory and practice. In this volume of proceedings the papers are arranged in the order in which they were presented at the conference.

Every Windsor Conference is special, each reflecting the then current concerns and new directions in which the study of thermal comfort was moving when they were held. Thermal comfort in hot climates has always been a particular area of interest here, not least because of a concern that main-stream research, centred on the use of air conditioning did not deal well with understanding comfort in such climates. With the increasing urgency of better understanding the physiological and psychological limits of comfort in a warming world, Session 8 covering "surveys in Hot Climates" was especially lively. Such was the feeling that populations in hot climates had much to teach the rest of the world that a group of researchers from the Gulf countries proposed a conference on 'Comfort at the Extremes' to be held in Dubai in April 2019. More of that later in the year on the Windsor Conference website.

Specialist scientific, semantic and technical concerns about survey methodology, and the scales and language used in them and even the very definition of comfort provided the basis for some serious discussions in the both the workshops and the sessions.

Since the first conference Windsor has fostered the growth of the adaptive approach to thermal comfort in both research and practice. There is an increasing realisation that providing comfort by using 'more machines and energy' will no longer solve the problem of keeping people thermally safe in buildings in the 21st Century. The idea of conditioning whole buildings to narrow temperature limits is increasingly seen as both unaffordable and uncomfortable for most of the world's population so the conference theme was very timely.

We quite simply have to re-think thermal comfort. How do we provide personal comfort in places where a number of people are gathered or working together? Ideas around personal comfort technologies and models were a 'hot topic' this year building on the growing imperative to heat and cool people rather than buildings, an approach that can also provide new opportunities to reduce costs by allowing people to manage their own personal thermal environments for comfort.

One way to reduce carbon emissions from buildings is to run them for as long as possible on ambient natural energy. This requires new comfort solutions for low energy and passive buildings. But to leave a positive legacy, new solutions must be built on good science, and the detailed understanding of it. That is why the Windsor Conference has been so successful and why it has had such an impact in many different fields. Its success and influence has been built on the trust established between its delegates, where people, often at the top of their profession, can bring new ideas and assumptions to have them intellectually bench-tested in a safe and respectful environment.

The people who come to Windsor are patently interested in building ethically better solutions, and demonstrably this year, approaches that recognise the growth in fuel poverty and increasing divisions between the rich and poor that occur everywhere today were highlighted.

New comfort paradigms are needed more than ever help deliver a safer thermal future for us all. The two keynote speakers at Windsor 2018 both heralded new ways forward, Kris De Decker of the Low-tech Magazine (www.lowtechmagazine.com) and Roberto Lamberts of the University of Santa Caterina, Brazil explored important narratives respectively of how we got to where we are today, how lessons from the past may well inform a different future, and how we can lay responsible research and legislative foundations for a very different future. These were powerful messages. We look forward to seeing you all at the Eleventh Windsor Conference in 2020 to take up and renew the debates from 2018.

Our thanks VELUX for sponsoring the opening reception. Their generosity will have helped to foster and develop our rethinking of Thermal Comfort in 2018.

ORGANISING COMMITTEE

Professor Fergus Nicol, London Metropolitan University (UK)
Professor Susan Roaf, Heriot-Watt University (UK)
Dr Luisa Brotas, London Metropolitan University (UK)
Reverend Professor Michael Humphreys, Oxford Brookes University (UK)
Will Finlayson, Heriot-Watt University (UK)
Anne Ormston, Heriot-Watt University (UK)

SCIENTIFIC COMMITTEE

All contributions to the 2018 Windsor Conference included herein were independently peer reviewed as a full paper, prior to publication. A special thank you to all reviewers.

Professor **Michael Adebamowo** University of Lagos (NG)
Professor **Edward Arens** University California, Berkeley (USA)
Professor **Li Baizhan** Chongqing University (CN)
Professor **Dr Philomena Bluyssen** Delft University of Technology (NL)
Dr **Atze Boerstra** BBA Binnenmilieu BV and Eindhoven University of Technology (NL)
Professor **Gail Brager** University of California Berkeley (USA)
Dr **Luisa Brotas**, London Metropolitan University
Dr **Bin Cao** Tsinghua University (CN)
Professor **Richard de Dear** University of Sydney (AU)
Professor **Andy Ford** London Southbank University (UK)
Professor **Rajat Gupta** Oxford Brookes University (UK)
Professor **Jake Hacker** Arup (UK)
Professor **George Havenith** Loughborough University (UK)
Dr **Gesche Huebner**, University College London (UK)
Reverend Professor **Michael Humphreys**, Oxford Brookes University
Dr. **Madhavi Indraganti** Univ Qatar (QA)
Dr **Boris Kingma**, TNO and Eindhoven University of Technology (NL)
Professor **Maria Kolokotroni** Brunel University (UK)
Professor **Risto Kosonen** Aalto University (FI)
Professor **Jarek Kurnitski** Tallinn University of Technology, (EE)
Professor **Alison Kwok** University of Oregon (USA)
Professor **Ashok Lall** Kamla Raheja Vidyanidhi Institute of Architecture and Environmental Studies (IN)
Professor **Roberto Lamberts**, Federal University of Santa Catarina (BR)
Professor **Wouter van Marken Lichtenbelt** Maastricht University (NL)
Professor **Dennis Loveday** University of Loughborough (UK)
Mr **Giancarlo Mangone** Delft University of Technology (NL)
Dr. **Azadeh Montazami** Coventry University (UK)
Professor **Fergus Nicol**, London Metropolitan University
Professor **Edward Ng** The Chinese University of Hong Kong (CN)
Professor **Marialena Nikolopoulou** University of Kent (UK)
Professor **Bjarne Olesen** Technical University of Denmark (DK)
Dr **Mark Olweny** Uganda Martyrs University (UG)
Professor **Ryozo Ooka** The University of Tokyo (JP)
Professor **Ken Parsons** Loughborough University (UK)
Professor **Jens Pfafferott** Hochschule Offenburg (DE)
Professor **Adrian Pitts** University of Huddersfield (UK*)*
Professor **Iftikhar Raja** COMSATS Institute of Information Technology (PK)
Professor **Hom Rijal** Tokyo City University (JP)
Professor **Susan Roaf**, Heriot-Watt University (UK)
Professor **Darren Robinson** University of Nottingham (UK)
Professor **Matheos Santamouris** University of Athens and University of New South Wales (GR)
Assistant Professor **Stefano Schiavon** University of California Berkeley (USA)
Dr **Marcel Schweiker** Karlsruhe Institute of Technology (DE)
Dr **David Shipworth**, University College London (UK)
Professor **Shin Ichi Tanabe** Waseda University (JP)
Dr **Despoina Teli**, University of Southampton (UK)
Dr. **Paul Tuohy** University of Strathclyde (UK)
Professor **Terry Williamson** University of Adelaide (AU)
Dr. **Peter Wouters** International Network for Information on Ventilation and Energy Performance (BE)
Professor **Da Yan** Tsinghua University (CN)
Professor **Runming Yao** University of Reading (UK)
Professor **Yingxin Zhu** Tsinghua University (CN)

TABLE OF CONTENTS

Papers in the table of contents have links to the associated paper in the book.
To go back to the table of contents press the image logo on the top on the paper.

AFTER DINNER TALK

Low-tech Comfort: Heating
People not Buildings

Kris de Decker

Invited Chair:
Fergus Nicol

SESSION 1

Rethinking Thermal Comfort

Invited Chairs:
Edward Ng and Luisa Brotas

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Puzzles and paradoxes in adaptive comfort

Michael A Humphreys[1] and J Fergus Nicol[2]

[1,2] Oxford Brookes University, UK, School of Architecture

Abstract: The welcome and widespread recognition that comfort is best seen as an interactive adaptive process has resulted in a proliferation of field study research. The analysis of the data from these studies, and attempts to formulate their results into guidelines and standards, has produced a number of puzzles that verge on the paradoxical: 1. Estimation of people's sensitivity to temperature-change by regression analysis appears to be logical, but often gives a misleading result; 2. The Griffiths method to obtain comfort-temperatures is sometimes necessary, yet its use entails apparently arbitrary choices; 3. The adaptive approach must be written into standards and codes, yet the concept of adaptation prohibits the stipulation of fixed values; 4. Is there a single worldwide relation between climate and comfort-temperature, or do we need numerous locally-derived relations? 5. Standard scales of subjective warmth help international comparisons, yet they often fail to translate across language and culture; 6. Humidity affects comfort, yet statistical analysis rarely captures its effect. The paper illustrates and examines several such puzzles.

Keywords: thermal comfort, field-studies, analysis

1. Introduction

The field-study is the primary method of researching adaptive thermal comfort. It relates objective environmental variables, such as temperature, thermal radiation, air movement and humidity to subjective responses such as the sensation of warmth and comfort, and the desire to feel cooler or warmer. A database is thereby developed where the subjective responses of one or a number of individuals are recorded simultaneously with the set of environmental variables. This type of data is often described as "right here, right now" expressing the fact that the data is linked to a particular time and place: not, for instance, relying on the memory of the individual or the use of a thermal index to predict the response. From the results of numerous field studies from different climates and cultures an overall pattern of human response to the thermal environment emerges.

Yet the interpretation of the results from such studies of thermal comfort can be difficult, and much depends on the analysis of the data being appropriate to the structure of the studies. Further difficulties can arise when meta-analyses are conducted, either in the attempt to encompass data from diverse cultures and climates into a single global model, or to develop standards applicable to a particular type of building or climate or to a country that has a variety of climates in its several regions.

It would be impossible in a paper of this length thoroughly to consider all the topics listed in the abstract. We do, however, give detailed attention to the difficulties that can be encountered in the use of regression analysis (topic 1 in the abstract), and the problems associated with the use of the Griffiths method (topic 2). The other topics we discuss more briefly, drawing attention to the nature of the difficulties that are encountered and suggesting ways in which progress might be possible.

2. Topic 1. Estimation of people's sensitivity to temperature-change by regression analysis appears to be logical, yet it often gives a misleading result.

A set of data from a field-survey of thermal comfort typically includes responses on a scale of subjective warmth (usually the Bedford scale or the ASHRAE scale) and the corresponding room temperatures. The usual method of extracting a sensitivity[1] to temperature-change is to estimate the regression coefficient of the subjective warmth (treated as an equal-interval scale) upon the room temperature. This statistical method was first applied to thermal comfort field-data by Thomas Bedford in his analysis of his large winter survey of thermal comfort in light industry (Bedford 1936).

It is one thing to point out the possibility of simple regression analysis failing to provide a plausible regression coefficient, and another to assess whether there is a real-life problem when handling thermal comfort field data. How common and how severe are problems with extracting regression coefficients from such data?

The problem is surprisingly common. The astonishing variety among the estimates of the regression coefficient can be illustrated by inspecting the values obtained from the ASHRAE RP-884 database of thermal comfort field surveys, which is one of the most reliable databases we have (de Dear et al 1998).

Figure 1 is a funnel-plot of the values of the regression coefficient for each of the many buildings represented in the database. Each point on the funnel-plot is the regression coefficient (subjective warmth on room temperature) from a survey in a single building in a single season. The horizontal axis is the value of the regression coefficient (scale-units per K) calculated for that building, while the vertical axis is the number of observations contributing to the regression. How well does the regression coefficient represent the sensitivity of the occupants to a change of room temperature?

Regression coefficients obtained from datasets with fewer than 50 observations range from minus 4.8/K to plus 2.5/K, and appear to be meaningless as estimates of the sensitivity of the respondents to changes in their room temperature. The funnel-plot also suggests, more surprisingly, that little credence can be placed on any individual value of the regression coefficient, even from a dataset with more than 300 observations, for even in these large datasets the coefficient can take any value between zero and 0.8/K.

Figure 2 is a histogram of the values of the regression coefficient, excluding sets with fewer than 50 observations. The values range from minus 0.1/K to plus 1.1/K – still an implausibly diverse set of values. The dashed line is the mean value, 0.35/K. This value seems reasonable, being close to the value of about 0.3 found from numerous experiments in fully-controlled climate-rooms. Perhaps it would be wiser to use a mean (or perhaps a median) value of the regression coefficients obtained from many field-surveys, rather than using a value obtained from any particular survey, to represent the sensitivity of the respondents to changes in their indoor temperature.

[1] By sensitivity we mean the change of the mean subjective thermal sensation of the group per unit change of the room temperature.

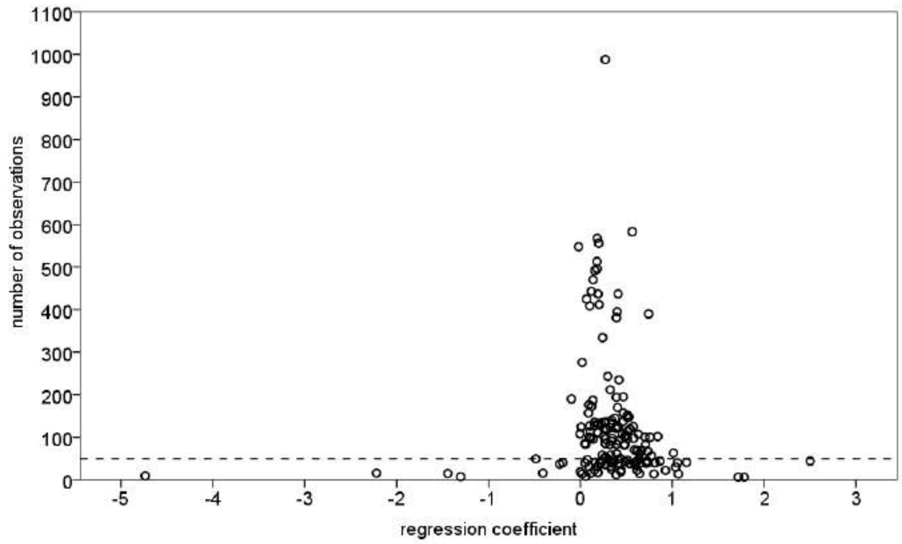


Figure 1. Funnel plot of the regression coefficients from buildings in the ASHRAE RP-884 database. (Source of figure: Humphreys et al 2016)

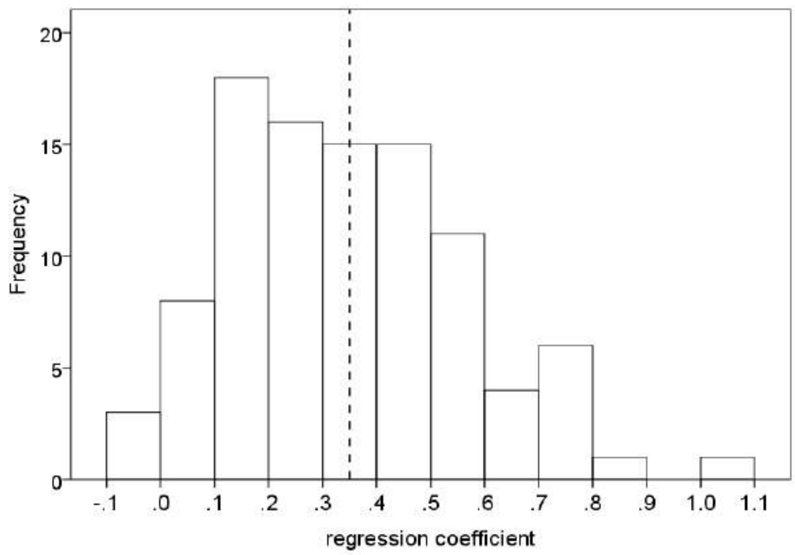


Figure 2. Histogram of regression coefficients (N>=50).
(source: Humphreys et al 2016)

Figures 1 and 2 demonstrate that there is a real practical problem, but they cannot indicate its source. The failure of the regression coefficient to provide reliable estimates of the sensitivity could be for one or more of a number of reasons:-

a) The set of data from which the regression equation is to be obtained may have too few observations, leading to a large uncertainty in the estimate of the regression coefficient.
b) The variance of the room temperature may be small, and the error in the measurement of the room temperature may be sufficient to substantially depress the estimate of the regression coefficient.
c) A field-survey may include observations from several different buildings. It is likely that these buildings (and even different rooms in a single building) will have different prevailing indoor temperatures, and it is also likely that the occupants will have to

some extent adapted themselves to these temperatures. A simple regression of warmth on temperature will then produce a misleadingly low value for the regression coefficient.

d) A database resulting from a field-survey project may include observations taken over a period of days, weeks or months. During the period of the survey the prevailing indoor temperature may change because of the weather and seasonal drift. It is likely that the comfort temperature will vary in sympathy with these changes. A simple regression of warmth on temperature may be quite misleading.

Much of the variation among the values of the regression coefficient noted above is attributable to one or more of these causes. We consider them in turn.

2.1. (a) Too few observations

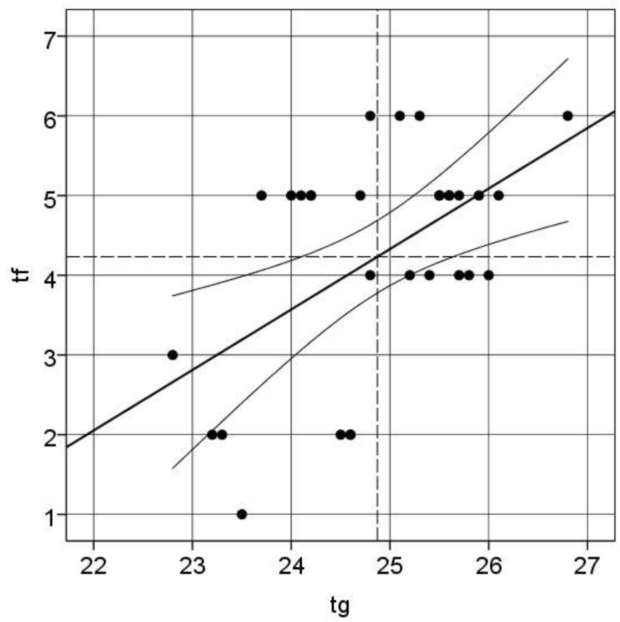


Figure 3. Example of a scatter-plot of thermal sensation on the ASHRAE scale (tf) (see table 1) and the room globe temperature (tg) at the time of the interview. (source: SCATs data, building U1, 6 Aug 1998, 26 observations)

Table 1. A seven-point descriptive scale commonly used in thermal comfort work. Note the numerical distance between the descriptors is assumed to be equal, but a number of researchers have queried this, in particular by demonstrating the difference between their meanings in different languages (see topic 5 below).

Descriptor	Number (tf)
Hot	7
Warm	6
Slightly warm	5
Neutral	4
Slightly cool	3
Cool	2
Cold	1

The example in figure 3 is from the European SCATs project (Nicol et al 2001), and is the data collected on a single day from an office-building in the south of the UK. Each observation is the thermal sensation (ASHRAE scale wording as shown in table 1) of a different person on the same day in the same building. The dashed lines are the means of the globe temperature and the thermal sensation. The vertical scatter of the observations about the regression-line is large, as is typical of thermal comfort data – not everyone feels the same at the same room temperature. The regression coefficient, although significantly different from zero, could be as low as 0.2/K or as high as 1.3/K, not a usefully precise estimate of the sensitivity of the people to temperature changes during the day.

2.2. (b) Small variance[2] of room temperature

If the variation of the room temperature during a field-survey is small, the accuracy of the estimate of the regression coefficient is correspondingly reduced. What is less obvious is that the presence of error in the predictor-variable biases downwards the estimate of the regression coefficient, giving the impression that people are less sensitive to temperature-change than they really are.

Figure 4 shows the effect of error in the predictor-variable (in our case the room temperature) on the least-squares estimate of the regression coefficient. The vertical axis is the ratio of the regression coefficient calculated by the least-squares procedure to its true value.

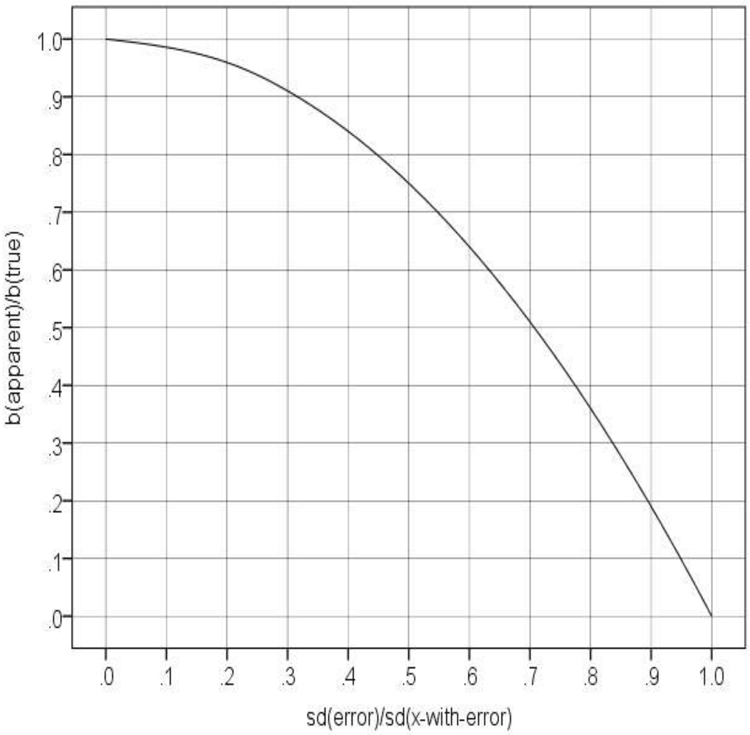


Figure 4. The effect of error in the predictor-variable on the least-squares regression coefficient. (Source: Humphreys et al 2016)

How common is it to find a small variation of room temperature during a field-survey? Again it is one thing to point out the possibility of there being a problem, and another to demonstrate that it is a common practical problem in our surveys.

The variation of room temperature during a survey is very often small, especially in heavyweight buildings, where the 'thermal mass' reduces variations of indoor temperature and the temperature will change slowly. Very little temperature-variation is found also in buildings with well-controlled heating or cooling systems.

[2] The variance is the square of a standard deviation.

Experience from numerous surveys indicates that the variance of the room temperature during a survey is often less than 1K. For example, in a pilot-study field-survey of the responses of small children, the standard deviation of the room temperature during the 12 days of the survey was a mere 0.7K (variance 0.49K^2).[3]

Again, the mean within-day within-building variance of temperature in the SCATs database is only 0.73K^2, giving a standard deviation of 0.87K (349 day-surveys). The corresponding figure for the ASHRAE RP-884 database is 0.83K (483 day-surveys). The temperature variation is in practice often very small indeed. So we need to consider whether the errors in the predictor are large enough much to affect the estimate of the regression coefficient.

There is of course always error in a measurement of temperature, or of any other predictor-variable we may use, such as Standard Effective Temperature (SET) (Gagge et al 1986) or the Predicted Mean Vote (PMV) (Fanger 1970). The practical question is whether the errors are large enough much to affect the estimate of the regression coefficient. It is useful to note the various kinds of error that might be present:

1. Random errors in the temperature readings, and, if several different instruments are used in the survey, systematic differences among them. With good quality instruments such errors are likely to be too small to matter.
2. Errors from the placing of the instrument. If it is too close to the respondent it will be affected by their body heat, while if it is too distant the temperature at that place may differ from the temperature where the respondent is.
3. Errors attributable to time-delays. In some experimental protocols the respondent is moved from the work-location after the interview, and the thermal environment then measured where the respondent had been seated. (It is impossible to measure exactly the conditions a respondent experiences. Either there are errors from differences in location, or there are errors from variations over time.)
4. There are also errors of a quite different kind. The temperature (usually either air or globe) is being used as a surrogate for a notional ideal index of warmth. In practice the room temperature is often quite a good approximation, but if we wish to improve on it we need a more complete index, such as SET (Standard Effective Temperature) or PMV. However, the random uncertainties introduced by the estimations of clothing insulation and metabolic rate when calculating these indices generally outweigh any advantage they bring. The error associated with an individual estimate of PMV has been shown to be some 0.74 of a scale-unit (Humphreys, Nicol & Roaf 2016, p 216) equivalent to about 2K, and about the same must apply to SET. So it seems we must choose between the errors arising from the index being a surrogate (we may call this 'equation error') or large random errors attributable to estimating clothing insulation and metabolic rate.

Error-variances of kinds 1, 2 and 3 are additive, but estimates of their magnitude are difficult to establish. However, an estimate of the random error arising from the placement of the instrument is available. From some 5000 paired observations in the ASHRAE RP-884 database, it can be calculated that the random component of the difference between the temperatures recorded by two good quality miniature globe thermometers placed a metre apart had a variance of around 0.16K^2 – a standard deviation of 0.4K. So, if we accept this figure as a provisional estimate of the standard deviation of the location-error in the globe

[3] A description of this study is found in Humphreys, Nicol & Roaf (2016) chapters 4 & 19.

temperature, we can use figure 4 to estimate the approximate size of the necessary correction to the regression coefficient.

If we take a typical field-study standard deviation of room temperature to be 0.85K (see above), the value on the horizontal axis of figure 4 is in the region of 0.5 (0.4/0.85). The regression coefficient calculated by least-squares regression will typically be only about three-quarters of its true value. We conclude that error in the predictor variable often leads to a substantial underestimation of the sensitivity of people to changes in the room temperature.

(A visual account of the effect of error in the predictor variable may be found in chapter 22 of Humphreys, Nicol & Roaf 2016, and a statistical treatment is found in Cheng & Van Ness 1999.)

2.3. (c) Different buildings

If the data from different buildings are included in the same simple regression analysis, and the mean temperatures in these buildings differ from one another, the regression coefficient obtained is unrealistically low. This is because people tend to adapt to the prevailing room temperatures they experience. The regression coefficient no longer represents the sensitivity of the occupants of any of the buildings, nor is it a mean sensitivity of them all. More generally, the pooling of surveys having differing mean temperatures, whether because of differences among the buildings or because of seasonal variation of indoor temperature, gives a misleading regression coefficient. The analysis must reflect the structure of the survey, if our aim is to discover the underlying sensitivity of the respondents to changes in their room temperature. A remedy is to analyse the data building-by-building, as in figures 1 and 2 above.[4]

2.4. (d) Seasonal drifts in prevailing mean room temperature

The same considerations apply to the analysis of data where there is a seasonal variation of room temperature. There is much to be said, if the aim is to find the sensitivity of the occupants to the short-term changes in room temperature they encounter, for breaking the data down into day-surveys. (People have been found to adapt less during their working day than they do from day-to-day, week-to-week or season-to-season.) A realistic value of the regression coefficient may then be calculated, either by taking the mean or the median of all the resulting regression coefficients, as suggested above, or by pooling the departures from the day-means of room temperature and thermal sensation into a single regression. In so doing, day-to-day, week-to-week and seasonal variations in mean room temperature are eliminated from the estimation of the regression coefficient. The regression coefficient then represents the average person's sensitivity to temperature-changes within the working day, and includes the effects of any adaptation that may have taken place during the day.

[4] Even this is not a complete remedy, for people adapt themselves not only to their building, but also to some extent to their particular space within it, so there remains some 'dilution' of the estimate of the sensitivity.

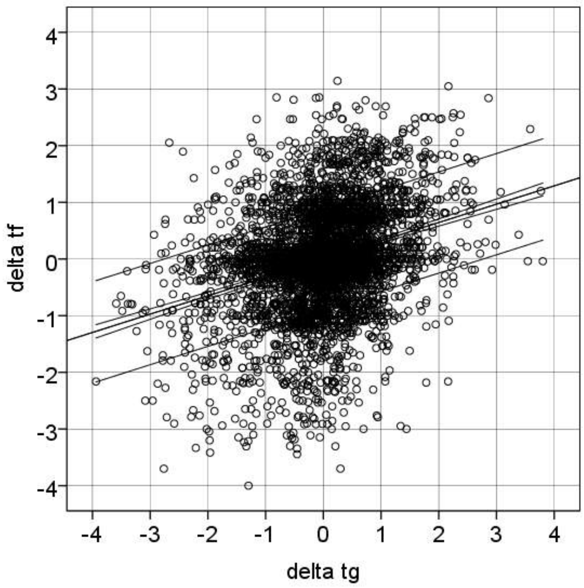


Figure 5. Pooled scatter-plot of the day-surveys in the SCATs database, showing the regression-line with its 95% confidence limits and the standard deviation of the residuals. (Source: Humphreys, Nicol & Roaf 2016)

Figure 5 shows the result of such an analysis for the day-surveys in the SCATs database. Despite the typically large variance of the thermal sensation (delta tf: departures from the day-mean of tf) and the small variance of room temperature (delta tg: departures from the day-mean of tg), the regression coefficient (0.37/K) can be obtained with sufficient accuracy. This is because of the large number of observations (N=3,318).

The value of the regression coefficient may then be corrected for the presence of error in the predictor-variable (delta tg) as discussed above. (In this example the correction raises the coefficient to 0.47/K)

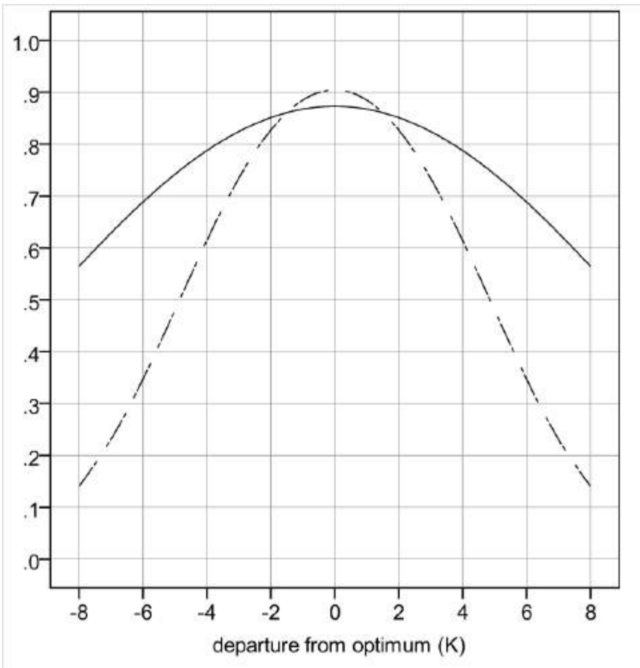


Figure 6. The effect of the statistical model on the estimated proportion of people in thermal comfort. The solid line is from the naïve model, the dashed line from the model that includes day-to-day, season-to-season and building-to-building effects. (source: Humphreys et al 2016)

The effect of disregarding the structure of the data when performing a regression analysis can be illustrated from the SCATs database. The naïve approach would be to perform a single regression analysis on the whole of the data. To do so is to ignore the structure of the data: the day-to-day, season-to-season and building-to-building effects. This naïve model gives a regression coefficient of 0.17/K compared with the value of 0.37/K when these effects are included in the model. The naïve approach is quite misleading, and the consequent effect on the estimates of the proportion of people in thermal comfort is severe (Figure 6).

2.5. Conclusion to topic 1.

A simple overall regression analysis of a thermal comfort database is likely to give a misleading result, if the regression coefficient is taken to represent the sensitivity of the occupants to changes in their room temperature during the day. A better procedure is to perform a within-building within-day regression analysis, and if necessary correct the regression coefficient for the presence of error in the predictor-variable.

3. Topic 2. The Griffiths method to obtain comfort-temperatures is sometimes necessary, yet its use entails apparently arbitrary choices.

3.1. Introducing the Griffiths method

How can we extract a neutral temperature from a small batch of data? A useful method was provided by Ian Griffiths, who had gathered numerous small batches of data from fieldwork in a variety of buildings across Europe (Griffiths c.1990). The regression coefficient from each small batch was unreliable. His answer was to *supply* the value for the regression coefficient.

The value he used came from numerous thermal comfort studies conducted in a climate-room with his co-worker Don McIntyre, during their years at the Electricity Council Research Centre in the UK. The value he and McIntyre had obtained for the sensitivity of people to room temperature changes was about 0.3 scale units per K – in good agreement with values obtained by Fanger in the studies that underlie the PMV equation (McIntyre 1980, Fanger 1970).

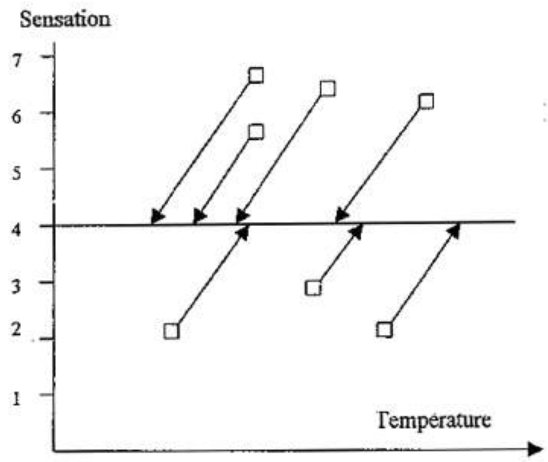


Figure 7. Schematic diagram to illustrate the Griffiths method of obtaining neutral temperatures. (source: Nicol et al 2012)

Using this value Griffiths could estimate a neutral temperature for even a single value of subjective warmth (see figure 7). The estimate from any single vote has a very low precision, but by averaging the values of the neutral temperature from each value of subjective warmth in a dataset, he could calculate a reliable neutral temperature, even from a small batch of data. This procedure has become known as the *Griffiths method*.

The method is subject to bias if the value chosen for the sensitivity (the Griffiths constant, as it has become known) is incorrect, and it may be that the artificiality of the climate-room experiments used by Griffiths caused people to respond differently. If so, we should not be using this value for the sensitivity. Different researchers have, in recent years, used a variety of different values. This makes the use of the Griffiths method seem rather arbitrary. This is a justified concern. However, if a correct value of the regression coefficient is used, the Griffiths method provides unbiased estimates of the neutral temperature.

We believe that a value based on fieldwork results should be used instead. But what value, or values, for the regression coefficient should be used? Griffiths did not have available a reliable value based on fieldwork, but since those days reliable estimates have become available (as shown under topic 1 above) based on a thorough analysis of all the day-surveys contained in the SCATs database and the ASHRAE database.

The mean values of the within-day within-building regression coefficients in these databases are 0.37/K and 0.38/K respectively – a remarkably good agreement between two entirely independent large databases (Humphreys, Rijal & Nicol 2013). Applying a correction for error in the predictor-variable raised the values to 0.47/K and 0.49/K. So it seems that people are considerably *more* sensitive to room-temperature changes in real life settings than they are in climate-room experiments. Most field-researchers, we believe, thought the opposite to be true – a belief arising perhaps from the common procedure of including in the same simple regression analysis data from various buildings over a period of days or weeks.

A summary-table of the within-day within-building regression coefficients is provided in table 2. People seem to be a bit more responsive to temperature-change in air-conditioned buildings, probably because of the cycling of the control-system. Also the ASHRAE data show that women are more responsive to temperature-change than are men (Figure 8). Whether this is attributable to physiological, psychological or to culture-based differences between men and women (or to both) is unknown. We suggest that the values from Table 1 be used when estimating neutral temperatures using the Griffiths method. These values will, of course, be subject to revision as new data are acquired and methods improved.

Table 2. Average sensitivities to room-temperature changes during the working day:[5]

	Women and men	Women	Men
All buildings	0.48	0.53	0.43
AC buildings	0.51	0.56	0.46
NV buildings	0.45	0.50	0.41

Notes: The values are group-averages. The units are scale-points per degree (/K), and assume a seven-point scale. The values are corrected for the presence of error in the predictor-variable. They apply to lightly active duties typical of office-work, and assume that the people are free to choose their clothing. AC: air-conditioned; NV: naturally ventilated.

[5] The derivation of the values in the table is found in Humphreys, Nicol & Roaf (2016) chapter 25.

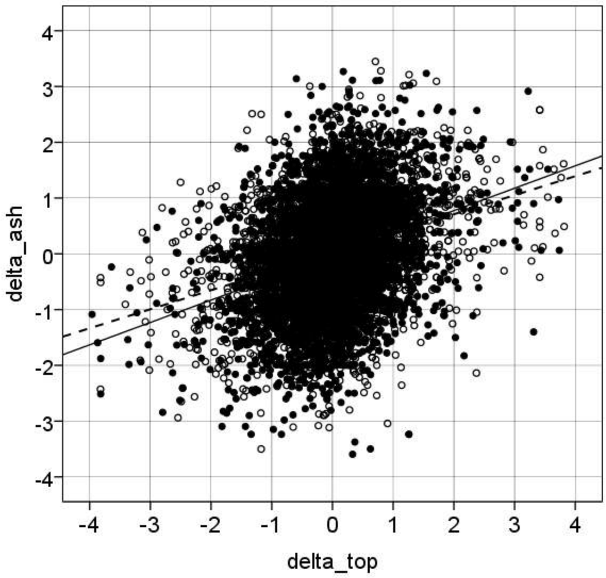


Figure 8. Comparing the sensitivity of men (solid line) and women (dashed line) in the ASHRAE RP-884 data (source: Humphreys et al 2016)

We therefore now have quite good working values of the regression coefficient to enter into the Griffiths method for calculating the neutral temperature from small batches of data. This overcomes the need to supply a value based on climate-chamber experiments when using the method.

3.2. Conclusion of topic 2

The Griffiths method should be used to estimate the neutral temperature if there are reasons to doubt the reliability of a regression coefficient obtained in a survey – reasons to which we drew attention above. Table 2 provides useful working values for the 'Griffiths constant'.

4. Topic 3. The adaptive approach must be written into standards and codes, yet the concept of adaptation prohibits the stipulation of fixed values.

The size and complexity of some current standards for the indoor environment is daunting. For example, ASHRAE Standard 55 now comes with a User's Guide of 141 pages. The complexity of the standard and the means of conforming to it are such that it is becoming difficult to be sure whether it can be complied with. The problem is made more difficult by the 'continual maintenance' of the standard, so that one is trying to comply with an ever-changing standard.

The adaptive approach to thermal comfort has found its way into some of the national and international standards for the thermal environment. It has been present in ASHRAE standard 55 since the 2004 edition. It has been present in standard CEN 15251 for Europe since 2007 (BSI 2007). It has a place in the all-China standard for thermal comfort (MOHURD, 2012). It appeared in the CIBSE Guide in the 1981 edition, and reappeared in 2006 and is in the current version (CIBSE, 2015).

Standards try to answer the question: What is the correct temperature for this room? How closely must this temperature be maintained? The question expects the answer to be a number – say, 22^{o}C±2.

The questions appear to be entirely straightforward, but they are not. Historically, winter temperatures for comfort have changed markedly over the last century, and the temperatures found to be comfortable differ according to culture and climate.

The adaptive approach to answering the question "How warm should this room be?" goes something like this:

> "Is the temperature normal (customary) for this culture in this season and in this type of accommodation? If so, it is likely that people are well-adapted to it and will find it comfortable. And if you give them a little bit of control over it, they will make themselves comfy – no problem."

This reply entails discovering and stating what temperatures are normal, and, if we aim to be ecologically responsible citizens, we try to use available constraints to 'nudge' the normal temperatures in a direction that would minimise energy use while achieving thermal comfort – a topic that would need another paper to explore!

Customary temperatures are established by some kind of cultural negotiation about what is fitting, and are subject to gradual evolutionary change over the years as various pressures from the culture act upon them, such as changes in energy costs, development in methods of heating and cooling, changes to the norms of building construction, and fashions in clothing. Our reply would also entail suggesting what possibilities for adjusting the thermal environment might be provided to accommodate the variation in a person's requirement from time to time, and the variety of that requirement among different people.

This means that an ideal adaptive standard for thermal comfort would be expressed very differently from the way current standards are expressed. Perhaps the way forward is to establish adaptive standards or guidelines alongside the current standards and guidelines, rather than seeking to change them. The specification for the indoor environment could say: the environment in the building shall conform to Adaptive Thermal Comfort Standard/Guideline XXX, rather than specifying ASHRAE standard 55, or another of the current standards.

4.1. Conclusion to topic 3

It may be that we should be advocating specifically adaptive standards and guidelines for achieving satisfactory conditions for thermal comfort, rather than continuing our efforts to introduce and maintain an adaptive element into standards that are based on heat exchange approaches to thermal comfort.

5. Topic 4. Is there a single worldwide relation between climate and comfort-temperature, or do we need numerous locally-derived relations?

For buildings operating in the free-running mode (FR) there is a strong relation between the temperatures found comfortable indoors and the prevailing outdoor temperature. In this mode neither heating plant nor cooling plant is used. Temperature-control is achieved by good climatic design, by admitting or excluding sunshine, by opening and closing windows, and by the use of fans to increase air movement. Figure 9 shows the comfort-temperatures from a recent meta-analysis plotted against the prevailing outdoor temperature. The comfort temperatures were obtained by the Griffiths method using a value of 0.5/K for the Griffiths constant. They are expressed either as air temperature or globe temperature, and no distinction was made between comfort temperature and neutral temperature. The measure of outdoor temperature was the best available for each of the surveys included in the database, either the daily mean as locally measured at the time, an exponentially weighted running mean, or data from meteorological tables.

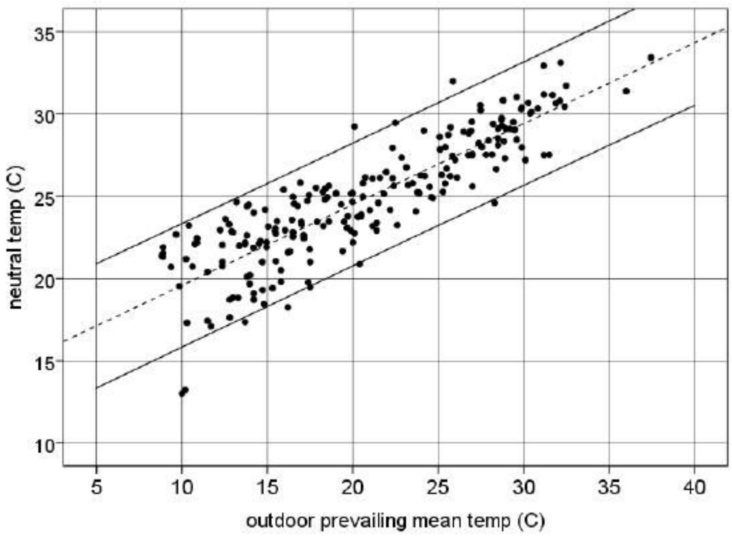


Figure 9. The relation between the indoor comfort temperature and the prevailing mean outdoor temperature form a database of summary statistics. Each point represents a separate survey or block of data within a larger survey. (source: Humphreys et al 2013)

The indoor comfort temperatures on the figure lie anywhere within a band rather than lying on a single ideal line. This variety of comfort temperature can be demonstrated in two ways. (1) The standard error of each estimate is small compared with the residual standard deviation of the points around the regression line, so the scatter about the line is not primarily error, but represents real differences among the possible comfort temperatures at each prevailing mean outdoor temperature. (2) The departures from the regression line (the residuals after regression) correlate with the departures of the mean indoor temperature from its average value at that prevailing outdoor temperature. These two considerations show that there is systematic structure within the band of apparent scatter. This leaves room for a local adaptive relation (sometimes called a local adaptive model or algorithm) to lie within the expected overall band, and yet be specific to its own region and dependent on certain features of the region's culture.

Thus new local adaptive models or algorithms may be researched and quantified, but we would expect them all to lie within the band indicated by the data collected from the numerous and diverse sources represented on figure 9.

For example we may wish to take the SCATs data as an adaptive relation encompassing the climate and cultures of the five European countries from which the data came, and, by extension, other countries of European culture and similar climate. Now, the SCATs data are included among the observations on the figure and all the comfort temperatures lie within the band, yet seen as an independent block, the adaptive model for Europe has a lower dependence on the prevailing outdoor temperature than does the overall band (0.33 compared with 0.53). So also, data collected from the seasons and climatic regions of Pakistan are included in the data and lie within the envelope of figure 9, yet the adaptive relation for Pakistan has a similarly low gradient (0.36) (Nicol et al 1996).

It remains to be seen whether the cultural factors can usefully be quantified and introduced to form a single overall model embracing the whole spread of climates and cultures of the world. This would be both intellectually satisfying and enable better estimates of comfort temperatures in regions where no field studies were extant.

In many buildings with powerful mechanical heating or cooling systems the indoor temperature is disconnected from the outdoor temperatures and the adaptive tendency will be to adapt the building to the occupants, rather than to adapting the occupants to the buildings as in free-running buildings. In dwellings this can result in an indoor climate which ranges more widely than in FR buildings (Nicol 2017).

5.1. Conclusion to topic 4

The presence of systematic structure within the envelope of the worldwide adaptive model for free-running buildings shown in figure 9 leaves room for sub-models specific to particular cultures, architectures and climatic ranges. This is of course to assume that such local models are based on sufficient local data, are representative of the populations and building stock, and that their analysis takes due regard of the experimental structure of the field-surveys.

6. Topic 5. Standard scales of subjective warmth help international comparisons, yet they often fail to translate across language and culture.

The history of thermal comfort field research shows that diverse scales of subjective warmth have been devised and used. The scales differ both in their wording and in the number of categories (scale-points). Some researchers have used as few as three categories; one has used as many as 25. In recent decades seven-category scales have become the norm, and the two most commonly used are the Bedford scale and the ASHRAE scale. Few researchers have investigated the behaviour of these scales in either their English language versions or when translated into other languages. Questions of interest include: do the scales behave as equal interval scales? That is to say, do the scale-categories have approximately equal psychological ranges? Do the translations have the same properties as the original scale? Regression analysis presupposes an equal interval scale, and international comparisons of results presuppose that the scale behaves the same when translated.

The psychological-interval property of a scale can be investigated by the method of successive categories. In this the cumulative proportions in the successive categories are transformed into Probits and their values plotted. If the intervals on the probit-scale are reasonably uniform, then the scale-categories have approximately equal psychological width. Using this method shows that in Bedford's original data the central category (comfortable) was very wide, and the categories 'comfortably cool' and 'comfortably warm' were narrow (Figure 10). This may have been caused by his method of successive questioning, which required the respondent to modify a previous reply that they were comfortable: Are you really comfortable, or would you prefer … slightly warmer or slightly cooler? So we notice that the properties of the scale might depend on the manner of questioning the respondents.

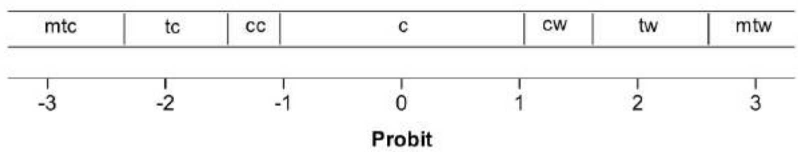


Figure 10. Comparing the psychological widths of the Bedford scale in Bedford's own data. (source: Humphreys et al 2016)

The approximate uniformity of the scale is of practical importance, because a Probit or logistic analysis using a scale that has irregular categories can give misleading information about the proportions of people in thermal comfort.

Problems with translated scales are not uncommon.[6] This is because the wording of the scale in English has been chosen in the context of concepts take for granted in English-speaking cultures, and these concepts may not be easy to render in another language. Thus, for example, the ASHRAE scale does not translate well into Japanese, and so the SHASE scale has been developed for use in Japanese-language surveys. The analysis of the SCATS data brought to light some problems with translation of the ASHRAE scale into French, Greek, Portuguese and Swedish.

Nowadays, with the internet, it is practicable to check the properties of a scale prior to its use. Such a check does not require any environmental measurements, but only a population similar to that proposed for the research project. It would be sufficient to obtain 1000 or so responses on the scale by an on-line enquiry, and then apply the method of successive categories – and if one had a bi-lingual population, the scale-as-translated could also be checked for its equivalence and its equal interval property. Being able to check the translation beforehand enables it to be modified and re-checked before conducting a large survey.

6.1. Conclusion to topic 5

The translation of the scales used in thermal comfort research deserves closer attention than it has normally received. A research aim should be the construction of a suite of scales that have been shown to be equivalent in the major languages in use today. This will greatly assist the inter-language comparison of research results.

7. Topic 6. Humidity affects comfort, yet statistical analysis rarely captures its effect.

There is currently something very unsatisfactory about the place of humidity in thermal comfort research. Heat exchange analysis shows that at moderate room temperatures and at low to medium levels of exertion, the humidity should have very little effect on thermal comfort, and this lack of effect is generally verified by results of field surveys of thermal comfort and also by results from climate chamber experiments. (This lack of effect is to be distinguished from the effect of humidity at high temperatures, when the human body is experiencing heat stress rather than just feeling slightly warm. At high temperatures the humidity can make the difference between the environment being habitable and being lethal.)

And yet people are convinced that the humidity is important for every-day comfort, and that they can say whether the atmosphere is humid or dry. Correlations between such subjective assessments of the humidity of the environment and the measured humidity are characteristically found to be very low or absent.

Most thermal comfort surveys include the measurement of humidity, and most often the output of the instrument is the relative humidity (RH) – a strange hybrid of temperature and vapour pressure. This is unfortunate, for the temperature component does indeed affect the sensation of warmth, so the analyst can be misled; finding an effect that disappears when, in further analysis, the temperature component of the RH is disentangled

[6] A discussion of the construction, translation and testing of thermal comfort scales is found in Humphreys, Nicol & Roaf (2016) chapters 18 & 19.

from the moisture component. Serious analysis should use the pressure of the water vapour in the atmosphere – absolute humidity (AH) rather than the RH.

Nicol (2017), when considering thermal comfort standards for hot and humid environments, reviewed the literature on effect of humidity on thermal comfort. He concluded that there was some evidence that, at higher absolute humidity, temperatures for comfort were very slightly lower, and that the humidity increased sensitivity to temperature change (the increase in the comfort-vote per degree rise in room temperature).

Yet it is difficult to believe that people's conviction that humidity has a pervasive and substantial importance for comfort is entirely groundless. It may be that the physical definition of humidity and the popular concept are entirely different. If so, a different approach is needed. We should be asking: what do people mean when they speak about humidity? In British English several words are used to describe the humidity the environment, such as: damp, dank, close, clammy, moist, humid, sticky. We could obtain estimates of the intensity of each of these sensations for a wide variety of physical environments and from a large number of people. Perhaps factor-analysis would reveal the structure of the replies, indicating the concepts that they contain. We would then be in a position to seek the physical correlates of the popular concept of humidity.

7.1. Conclusion to topic 6

It may be that we should reverse our approach to the analysis of the effect of humidity on thermal comfort, starting by analysing the vocabulary people use, and only then seeking physical correlates. We may then find that they are talking of something real, but different from the physicist's definition of humidity.

8. Concluding comment

We have been unable in this wide-ranging discussion to deal at length with all the topics mentioned, but we hope we have we have said enough to stimulate discussion. Fuller treatment has been given to explaining the vagaries of the estimation of the regression coefficient – the sensitivity of people to a changing room temperature – and to the proper use of the Griffiths method for extracting comfort-temperatures from field-survey data. Both of these are currently live topics among thermal comfort field-researchers.

9. References

ANSI/ASHRAE Standard 55-2013: *Thermal environmental conditions for human occupancy*. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Atlanta, Georgia, USA, 2013.

Bedford, T., 1936. *The warmth factor in comfort at work.* Medical Research Council Report no. 76, HMSO, London (110pp).

BSI, 2007. BS EN 15251: 2007 *Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics.* (Brussels: Comité Européen de Normalisation).

Cheng, C.L. and Van Ness, J.W., 1999. *Statistical Regression with Measurement Error*. Kendall's Library of Statistics, Volume 6, Arnold, London.

CIBSE, 2006. Guide A *Environmental Design* (London: Chartered Institution of Building Services Engineers).

de Dear, R., Brager, G. and Cooper, D., 1997. *Developing an adaptive model of thermal comfort and preference.* Final Report on RP-884. Macquarie University, Sydney, Australia. (296pp).

Fanger, P.O., 1970. *Thermal Comfort*. Danish Technical Press, Copenhagen.

Gagge, A.P., Fobolets, A.P.R. and Berglund, L.G., 1986. A standard predictive index of human response to the thermal environment. *ASHRAE Transactions*, 92(2b), 709-731.

Griffiths, I.D. (undated, circa 1990) *Thermal comfort in buildings with passive solar features: field studies*. Report to the Commission of the European Communities ENS3S-090-UK, Department of Psychology, University of Surrey, UK.

Humphreys, M., Nicol, F. and Roaf, S., 2016. *Adaptive thermal comfort: foundations and analysis.* Routledge 2016

Humphreys, M.A., Rijal, H.B. and Nicol, J.F., 2013. Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. *Building and Environment*, 63, 40-55 (http://dx.doi.org/10.1016/j.buildenv.2013.01.024)

ISO, 2005. ISO 7730: *Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.* ISO Geneva.

McIntyre, D.A., 1980. *Indoor climate.* Applied Science Publishers, London.

MOHURD, 2012. *National standard of the People's Republic of China: Evaluation standard for indoor environment in civil buildings.* (English translation GB/T 50785 – 2012)

Nicol, J.F. and McCartney, K.J., 2001. *Final Report (Public) Smart Controls and Thermal Comfort (SCATs)* (also subsidiary reports to tasks 1-7). Report to the European Commission of the Smart Controls and Thermal Comfort project (Contract JOE3-CT97-0066), Oxford Brookes University, UK.

Nicol,F., Humphreys, M. and Roaf, S., 2012. *Adaptive thermal comfort: principles and practice*. Routledge, 2012 (pp173).

Nicol, F., Raja, I. and Alauddin, A., 1996. *Thermal Comfort in Pakistan II*. Report to the Overseas Development Administration. School of Architecture, Oxford Brookes University, UK. (pp92)

Nicol, J.F., 2017. Temperature and adaptive comfort in heated, cooled and free-running dwellings. *Building Research and Information*, vol. 45(7).

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Thermal adaptation and seasonal alliesthesia: Two conflicting concepts?

Marcel Schweiker[1,2], Susanne Becker[2,3] and Karin Schakib-Ekbatan[2]

[1] Karlsruhe Institute of Technology, Germany, marcel.schweiker@kit.edu;
[2] Heidelberg Academy of Sciences and Humanities, Germany
[3] Central Institute of Mental Health Mannheim, German, susanne.becker@zi-mannheim.de

Abstract: Leaving the static view on thermal comfort, two concepts are presented in the literature: adaptation and alliesthesia. So far, there was no comparison between the consequences of these two concepts. However, their basic hypothesis related to preferred conditions in different seasons are antithetic – while adaptation suggests warmer conditions in summer being closer to neutrality – often set synonymous with comfort – alliesthesia suggests cooler conditions in summer leading to a higher level of pleasure – also set synonymous with comfort. The objectives of this paper are to compare both concepts and the resulting views on “optimal” thermal conditions by means of an experimental study. The experimental study consisted of a between-subject design with two groups (winter (N=32) and summer (N=31)) experiencing the same three thermal conditions (classified as cool, neutral, warm) each for 50 minutes in a balanced order in a field laboratory with windows to the outdoors. Subjects voted their thermal sensation and thermal pleasure at the end of each session. Indoor environmental parameters and subjects’ skin temperature were recorded. Analyses showed that thermal sensation assessed by the ASHRAE scale followed the assumptions of the adaptive approach: subjects perceived the warm conditions slightly less warm in summer. Thermal pleasure had its maximum at slightly cool conditions in summer and at slightly warm conditions in winter. Skin temperature variations did not explain such seasonal difference in the perception. Yet, it is hypothesized that a new mode of alliesthesia can explain such effects: seasonal (or long term) alliesthesia. In conclusion, adaptation and alliesthesia focus on different dimensions of thermal perception and lead to distinctive results concerning the optimum thermal conditions. The consequences for the operation of buildings is a challenging discussion to be continued with future research work.

Keywords: Thermal comfort, adaptation, alliesthesia, experimental study

1. Introduction

Leaving the static view on thermal comfort underlying many models, two concepts are discussed in the literature on thermal comfort: adaptation and alliesthesia.

What is known these days as the adaptive model of thermal comfort, has its origins in the work of Humphreys (1978, 1976) and Auliciems (1981). Humphreys (1978) showed a relationship between monthly mean outdoor temperature and neutral temperature similar to the one later applied in ASHRAE 55-2004 (2004). Auliciems (1981) already mentioned the effect of psychological adaptation, which is one of the three adaptive principles described by de Dear, Brager and Cooper (1997) together with behavioural and physiological adaptation. According to the adaptive model of thermal comfort, adaptation to warm conditions leads to a higher “neutral temperature for thermal comfort” (Humphreys, 1978, p. 102).

The term *alliesthesia* was proposed by Cabanac (1971) as a combination of “esthesia (meaning sensation) and allios (meaning changed)” (p. 1105) and described by the observation that “the pleasure or displeasure of a sensation is not stimulus bound but depends on internal signals” (p. 1102). While Cabanac (1971) already mentioned thermal stimulations, it was only later that this topic was picked up again and its relevance shown for the field of thermal comfort in buildings (de Dear, 2011; Zhang et al., 2010; Parkinson and de Dear, 2015; Parkinson, de Dear and Candido, 2016; Parkinson and de Dear, 2016, 2017). The concept of alliesthesia yields that e.g. a person being in a thermal state above thermal neutrality would perceive a cold stimulus – leading towards thermal neutrality – as pleasant.

The two brief descriptions of adaptation and alliesthesia already reveal some potential discrepancy in their effect: while adaptation assumes warm temperatures in summer to be sensed closer to neutrality – also referred to as "comfortable" – alliesthesia predicts a cool stimulus to be pleasant – also referred to as "comfortable" – in a warm environment. Due to this potential discrepancy, it is worth comparing these two concepts, which leads to the two main research questions of this paper:

1) Are the two concepts referring to the same dimension of thermal comfort?
2) Do both concepts lead to the same thermal conditions regarded as "optimum", i.e. can both be regarded as valid measures of the same construct of thermal comfort?

In order to answer these questions, a discussion on the various terms used in the literature on thermal comfort and in above descriptions is necessary. Such discussion is in parts presented in de Dear (2011), but due to its relevance for this paper extended in the following. De Dear (2011) refers to Cabanac (1992) with the statement that:

"The distinction between thermal sensation and thermal comfort echoes the psychologists' dichotomy between sensation and perception (Cabanac, 1992). Sensation is regarded as the detection of a stimulus in the environment, whereas perception refers to the way in which one interprets that information." (de Dear (2011), p. 110).

At the same time, fundamental textbooks in psychology agree that sensation is the process of sensing a stimulus and sending the corresponding information to the brain; while perception is the interpretation of this information (see e.g. Heffner, 2001). In contrast to de Dears' statement above, also thermal sensation – as the expression of the intensity and direction of a thermal stimulus from cold over neutral to warm – must be regarded as a perception and as influenced by the recipients', e.g. a subjects', interpretation of the signals from the thermal sensors. What are the consequences? Thermal sensation, including thermal neutrality, thermal pleasantness, as well as thermal preference, thermal acceptability, and thermal comfort must be regarded as different dimensions of the perception of the thermal environment (see also Schweiker et al. (2017) for a discussion on different dimensions of thermal perception). Relevant for this paper looking at adaptation and alliesthesia are the dimensions sensation and pleasantness.

Related to adaptation, Humphreys (1978) based his neutral temperature on those measured air- or globe temperature values "found to be 'neither warm nor cool', neutral, or 'comfortable'" (p. 94). De Dear, Brager and Cooper (1997) used as neutral indoor operative temperature the result of setting the thermal sensation vote (TSV) to zero in a linear regression model between operative temperature as predictor and TSV as neutral temperature. Therefore, adaptation was so far assessed mainly through the sensation vote.

Related to alliesthesia, de Dear (2011) describes comfort as "the hedonic tone or pleasantness of the stimulus (like versus dislike)" (p. 110) and uses in own studies a scale ranging from "very unpleasant" to "very pleasant" (Parkinson, de Dear and Candido, 2016).

Related to the first research question of this paper, this implies that adaptation and alliesthesia must be assessed by two different dimensions of thermal perception. Based on above-mentioned, the following hypotheses are postulated:

Due to adaption, warm conditions will not be perceived as intense (warm) in summer compared to winter. This can be seen e.g. in the adaptive comfort equations, which are based on sensation votes alone (de Dear, Brager and Cooper, 1997; Humphreys and Nicol, 1998). Similarly, repeated cold stimuli can lead to cold adaptation (van der Lans et al., 2013; Van Ooijen et al., 2004) in winter.

Hypothesis 1 (H1):Therefore, H1 states that the same warm conditions lead to a lower thermal sensation vote in summer than in winter..

Hypothesis 2 (H2): Following the same logic as H1, H2 states that the same cool conditions should lead to a thermal sensation vote in winter closer to neutrality than in summer.

From the alliesthesial point of view, pleasantness is highest during the transition of conditions likely restoring thermal neutrality. In winter, the risk for deviations from thermal neutrality to the cold are more likely, so that warm conditions could be regarded in general as more pleasant (favoured). In summer, the risk of (over)heat(ing) of the body has a higher probability so that cooler conditions could be favoured and leading to a higher level of pleasantness.

Hypothesis 3 (H3): Therefore, H3 states that in winter, the same warm conditions will be evaluated as more pleasant than in summer.

Hypothesis 4 (H4): Following the same logic as described in H3, H4 states that the same cool conditions should be more pleasant in summer than in winter.

This paper addresses these hypotheses by comparing the effects of adaptive and alliesthesial processes on the thermal sensation and thermal pleasantness votes given by human subjects in reaction to three distinct indoor thermal conditions (cool, neutral, and warm) during two different seasons (summer and winter).

2. Method

The experimental study consisted of a between-subject design with two groups staying in the same three thermal conditions (cool, neutral, warm) each for 50 minutes in a balanced order as explained below and in detail in Fuchs et al. (2018).

2.1. Subjects

Sixty-three healthy participants took part in the study: 32 in January and February 2016 (winter) and 31 in July and August 2016 (summer). The demographic characteristics of the samples are summarized in Table 1. Statistical tests show no significant difference between the two groups in terms of demographic (sex and age) and physiological (weight and height) characteristics.

Table 1. Description of the sample

	Winter		Summer	All
N (subjects)	32		31	63
Sex	18 female/ 14 male	X^2 = 0.14, df = 1, p = 0.71 [a)]	15 female/ 16 male	33 female/ 30 male
Age	25.2 ± 2.7	t = 1.4, df = 61, p = 0.17 [b)]	24.2 ± 2.7	24.7 ± 2.7
Weight	66.7 ± 12.2	t = -0.75, df = 61, p = 0.46 [b)]	69.1 ± 12.9	67.9 ± 12.5
Height	173.6 ± 9.4	t = -0.073, df = 61, p = 0.94 [b)]	173.7 ± 8.4	173.6 ± 8.8

[a)] 2-sample test for equality of proportions with continuity correction

[b)] Welch Two Sample t-test

2.2. Data acquisition

The study took place in the field laboratory LOBSTER (Laboratory for Occupant Behaviour, Thermal comfort, Satisfaction and Environmental Research) belonging to the Building Science Group, Germany.

After the subjects were welcomed, instructed and their written informed consent was obtained, they were interviewed about their interpretation of words and phrases used in thermal comfort research. For example, they were asked about the position of the label "warm" on a scale ranging from comfortable to uncomfortable (see Fuchs et al. (2018) for details and results). Following this interview, the participants started the series of above-mentioned distinctive thermal conditions. Based on a priori calculations of predicted mean votes (PMV) (Fanger, 1970), these conditions were classified as either "cool" (PMV -1.5 with operative temperature (T_{op}) 20°C, air speed (v_a) <0.1 m/s, relative humidity (rh) 50%, metabolic rate (met) 1.1 met, clothing level (clo) 0.6 clo), "neutral" (PMV 0.3 with 25°C, <0.1m/s, 40%, 1.1met, 0.8 clo) or "warm" (PMV 1.6 with 30°C, <0.1m/s, 30%, 1.1met, 0.8 clo). The participants experienced each condition for around 50 minutes.

After 45 minutes, the participants had to fill out a comfort questionnaire, consisting among others of the 7-point ASHRAE thermal sensation vote together with six visual analogue scales (VAS) (thermal sensation, pleasantness, acceptability, comfort, preference, and tolerance) of which thermal sensation ("cold" to "hot") and thermal pleasure ("not pleasant" to "pleasant") are relevant for this paper.

Indoor and outdoor environmental parameters were logged in a one-minute interval, and the clothing insulation level was assessed by means of a questionnaire in combination with the values given in ISO 7730 (2005).

In addition, skin temperature was assessed at 4-points (neck, shoulder, hand, shin) according to ISO 9886 (2004) using iButtons.

2.3. Data preparation and analysis

Before the data analysis, the following variables were derived:

- PMV: The PMV was used as a single variable to describe characteristics of the indoor thermal environment. It was calculated using the R-package comf (Schweiker, 2016) and as input parameters the measured values for T_{op}, rh, and v_a, the assessed clothing insulation level, and an assumed metabolic rate for seated activities of 1.1 MET according to ISO 7730 (2005).

- T_{sk}: Mean skin temperature (T_{sk}) was calculated according to ISO 9886 (2004), Table B.1, using the measured values.

The data was analysed with the software R (R Development Core Team, 2012).. Independent variables were the PMV, sex, and season. The factor sex was included due to findings regarding differences in the perception of indoor thermal environments between females and males (see e.g., Kingma and van Marken Lichtenbelt, 2015). As dependent variable, one out of the value of thermal sensation obtained by the ASHRAE scale or VAS rating, thermal pleasure from the VAS rating, or T_{sk} was assessed. The subject identifier was included as random effect to each model, because the data included three votes from each participant so that the assumption of independence required to use a linear regression model was not met. Quantile-comparison plots for each dependent variable revealed that normal distribution describe the data best compared to log-normal, binomial, poisson distribution. Therefore linear mixed effect regression analysis was applied and implemented with function lmer from the R-package lme4 (Bates et al., 2014).

First, for each model, it was analysed whether a polynomial model leads to a better fit between PMV and the dependent variable. P-values were obtained through a log-likelihood test of a base model (including only the first order polynomial of PMV) with the extended model (including first and second order polynomial of PMV).

Second, it was tested whether the addition of the factors season (levels “summer” and “winter”), sex (levels “female” and “male”) and their interactions were significant based on a type II Wald X^2-test.

3. Results

Table 2 presents the results for the comparison between first and second order polynomial models for each dependent variable. A significant result signifies that the second order polynomial model leads to a better model fit, which is only the case for the dependent variable pleasure.

In the second step, linear trends are analysed for thermal sensation and a quadratic trend for pleasure and T_{sk} based on these results.

Table 2. Results of log-likelihood tests comparing first and second order polynomial models (Format: X^2 (degrees of freedom): p-value)

Dependent variable	AIC (1^{st} / 2^{nd} order model)	ANOVA results
Sensation (ASHRAE)	437.6 / 438.6	1.02 (1): .31
Sensation (VAS)	1455.4 / 1457.4	0 (1): 1.00
Pleasure	1797.0 / 1765.9	**33.1 (1): <.0001***
T_{sk}	274.6 / 272.6	**3.97 (1): .046***

3.1. Thermal sensation

Figure 1 shows individual data points together with the regression lines for thermal sensation observed through the ASHRAE scale for each season and sex. Table 3 summarizes the corresponding model parameters. Here and in the following sections, only the highest order interactions being significant will be interpreted.

The calculated value of PMV, the sex, and the interaction between PMV and season (PMV:season) have a significant effect on thermal sensation votes. The non-standardized effect size of PMV on thermal sensation is around 1, i.e. for an increase of 1 unit of the calculated PMV, the thermal sensation increases by 1 unit as well. Males rate their thermal sensation 0.4 units higher compared to females. The interaction PMV:season leads to more intense (warmer) sensation votes at warm conditions during winter compared to summer, while it leads to less intense (cooler) sensation votes at cold conditions during winter compared to summer.

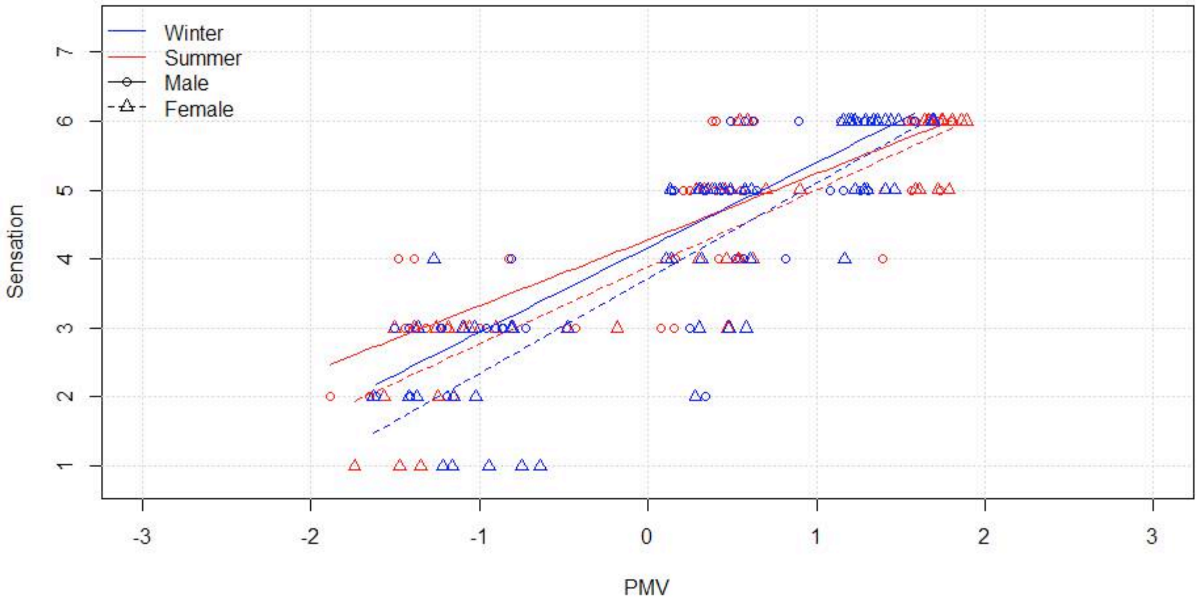


Figure 1. Relationship between calculated PMV and thermal sensation observed through the ASHRAE scale (1 = cold, 2 = cool, 3 = slightly cool, 4 = neutral, 5 = slightly warm, 6 = warm, 7 = hot).

Table 3. Model parameters for linear mixed effect regression models including the factors sex and season for thermal sensation obtained through the ASHRAE scale (model: AIC 430.9, R^2 (full): 0.85, R^2 (fixed effects): 0.73).

Variable	Coefficient	Std.error	$X^{2\ a)}$	p-value
Intercept	3.88	0.15		
PMV	1.12	0.08	678.3	**<.0001***
Sex (male)	0.40	0.20	6.80	**.009***
Season (winter)	-0.16	0.19	0.04	.83
PMV:Sex	-0.16	0.12	3.01	.08
PMV:Season	0.26	0.12	8.83	**.0030***
Sex:Season	0.05	0.28	0.03	.85
PMV:Sex:Season	0.01	0.18	0.003	.95

a) degrees of freedom are always 1

The results related to thermal sensation assessed through the VAS scale are presented in Figure 2 and Table 4 and different to those from the ASHRAE scale. In contrast to the results obtained through the ASHRAE scale, the season and interaction between PMV and sex are significant, but the interaction between PMV and season is not significant. The latter leads to the regression lines in Figure 2 approaching each other but not crossing each other between a PMV of 0 and 1 as in Figure 1.

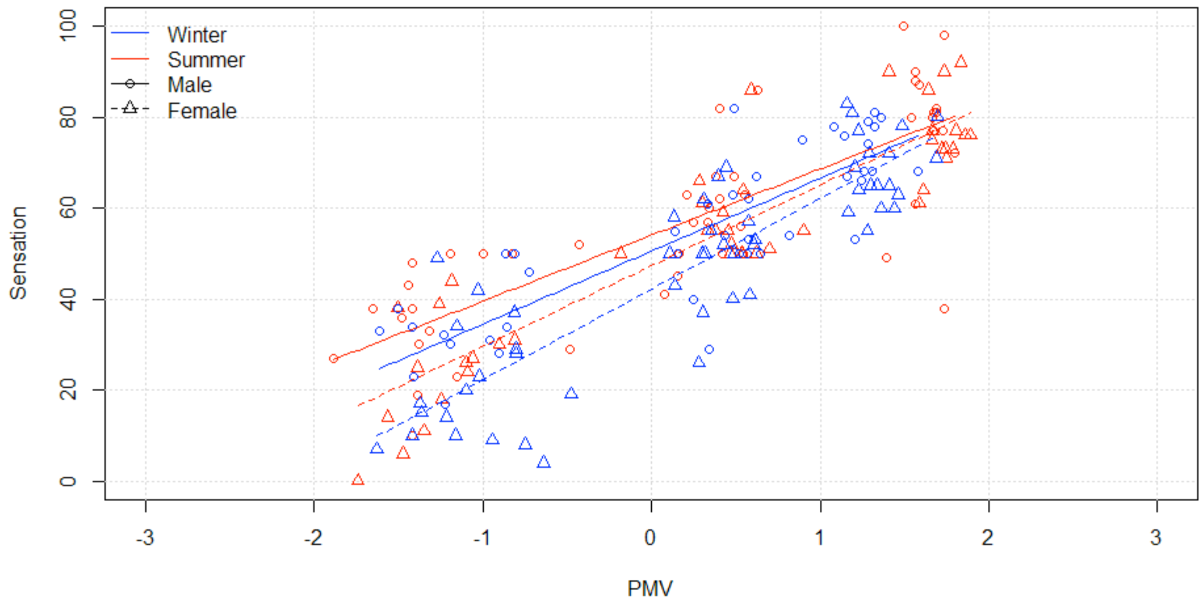


Figure 2. Relationship between calculated PMV and thermal sensation observed through the VAS scale (0 = cold, 100 = hot).

Table 4. Model parameters for linear mixed effect regression models including the factors sex and season for thermal sensation obtained through the VAS scale (model: AIC 1444.7, R^2 (full): 0.94, R^2 (fixed effects): 0.75).

Variable	Coefficient	Std.error	$X^{2\ a)}$	p-value
Intercept	47.4	1.92		
PMV	17.7	1.58	454.2	**<.0001***
Sex (male)	6.7	2.67	14.1	**.0002***
Season (winter)	-5.1	2.60	4.90	**.027***
PMV:Sex	-3.2	2.20	4.72	**.030***
PMV:Season	2.2	2.21	1.33	.25
Sex:Season	1.6	3.75	0.16	.69
PMV:Sex:Season	-0.66	3.23	0.04	.84

[a)] degrees of freedom are always 1

3.2. Thermal pleasure

The calculated value of PMV, the interaction between PMV and sex (PMV:sex), and the interaction between PMV and season (PMV:season) have a significant effect on thermal pleasure as shown in Figure 3 and Table 5.

The effect of the interaction PMV: sex leads to males stating a higher level of pleasure at lower values of PMV and a slightly different shape of the regression curve compared to females. The non -standardized effect size of the interaction PMV:sex is a shift of the peak perception of pleasure of 1 unit of PMV.

The effect of the interaction PMV:season leads to the peak perception of pleasure being at a higher value of PMV, i.e. warmer conditions, in winter compared to summer. The non-standardized effect size of the interaction PMV:season is a shift of the peak perception of pleasure of 0.5 units of PMV for females and 1 unit for males.

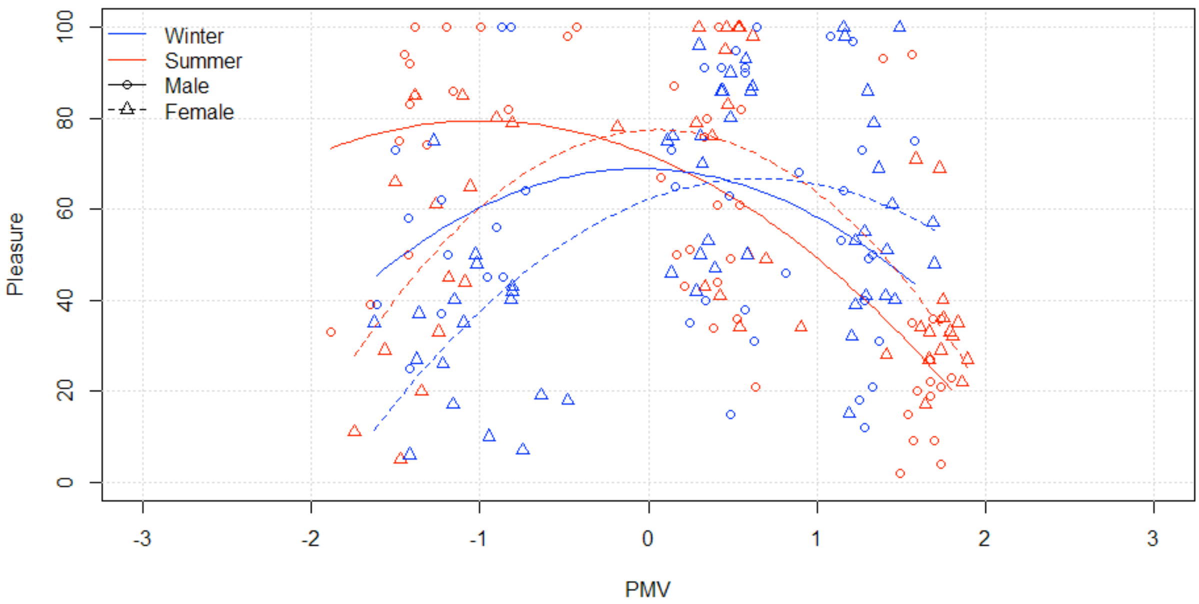


Figure 3. Relationship between calculated PMV and observed thermal pleasure (0 = .not pleasant, 100 = pleasant)

Table 5. Model parameters for linear mixed effect regression models including the factors sex and season for thermal pleasure (model: AIC 1740.8, R^2 (full): 0.54, R^2 (fixed effects): 0.10).

Variable	Coefficient	Std.error	X^2	p-value
Intercept	57.8	3.45		
PMV	-21.2	46.4		
	-213.1	38.6	53.9 (2)	**<.0001***
Sex (male)	0.29	4.78	1.97 (1)	.16
Season (winter)	-5.78	4.70	3.00 (1)	.08
PMV:Sex	-232.3	64.5		
	108.1	53.5	24.3 (2)	**<.0001***
PMV:Season	201.8	66.9		
	66.6	62.6	18.6 (2)	**<.0001***
Sex:Season	3.81	6.84	0.42 (1)	.51
PMV:Sex:Season	7.87	99.1		
	-94.4	95.2	1.01 (2)	.60

3.3. Skin temperature

As shown in Figure 4 and Table 6, the calculated PMV and the interaction between PMV and season (PMV:season) have a significant effect on skin temperature. The non-standardized effect size of less than 0.3 units of PMV can be regarded as small. In addition, it should be noted that even though the interaction with sex is not significant, the direction of the effect is oppositional; while females have a higher skin temperature at a given value of PMV in winter, males have a higher skin temperature in summer.

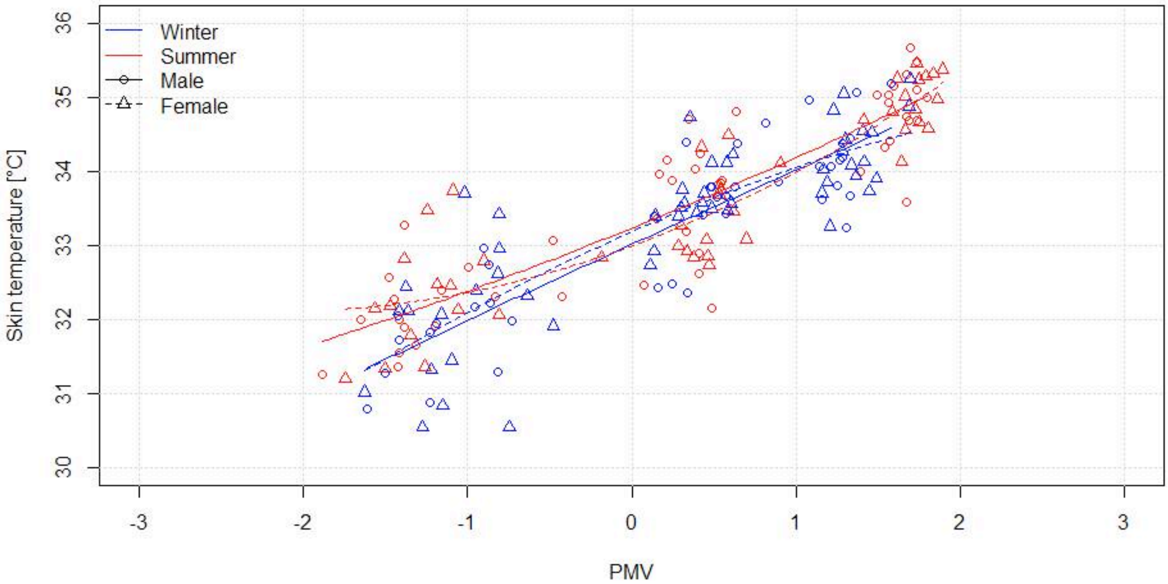


Figure 4. Relationship between calculated PMV and observed skin temperature.

Table 6. Model parameters for linear mixed effect regression models including the factors sex and season for skin temperature (model: AIC 271.0, R^2 (full): 0.96, R^2 (fixed effects): 0.77).

Variable	Coefficient	Std.error	X^2	p-value
Intercept	33.4	0.13		
PMV	12.91	0.77		
	2.56	0.60	1289.0 (2)	**<.0001***
Sex (male)	0.09	0.18	0.09 (1)	.77
Season (winter)	-0.15	0.18	1.13 (1)	.29
PMV:Sex	0.96	1.07		
	-1.89	0.84	2.38 (2)	0.30
PMV:Season	1.61	1.11		
	-4.10	1.00	16.2 (2)	**.0003***
Sex:Season	-0.12	0.25	0.46 (1)	.50
PMV:Sex:Season	-0.09	1.63		
	3.22	1.51	4.55 (2)	.10

4. Discussion and conclusions

The results shown above imply that adaptation affects the perception of thermal sensation and alliesthesia that of thermal pleasure.

H1 is confirmed by the results from the thermal sensation assessed by the ASHRAE scale; the intensity of warm conditions is slightly less intense at warm conditions during summer experiments compared to winter experiments. It should be highlighted that this observation was made despite limited adaptive opportunities during the experiments. The clothing level was prescribed by the experimental conditions and no behavioural adaptive actions such as adjusting clothes or opening windows were allowed and performed by the participants. Therefore, the observed adaptation in thermal sensation votes can be assigned to physiological adaptation through adjustments of sweat patterns (see e.g. Hori, 1995) and/or psychological adaptation such as changed expectations or preferences. The results based on the ASHRAE scale presented in this paper, confirm seasonal differences in the perception of the intensity. However, the authors argue that future studies are necessary in order to reveal whether such differences are due to different perceptions of the same intensity expressed on the thermal sensation scale or due to different interpretation of the semantics.

The results based on the VAS scale do not confirm this interpretation so that a final conclusion requires additional studies related to the validity of the thermal sensation assessed by both scales. As long as there is no procedure to reliably match thermal sensation between the ASHRAE scale and VAS scale, any comparison needs to be done with great care.

In line with hypothesis 3, thermal pleasure varied between seasons and was in summer highest at cooler conditions compared to winter. Variations in skin temperature cannot explain such variation as shown above. In previous literature, two modes of alliesthesia have been described: temporal, i.e. due to different thermal conditions experienced within a short time series, and spatial, i.e. due to different thermal conditions at different body zones, (Parkinson and de Dear, 2016, 2017, 2015; Parkinson, de Dear and Candido, 2016). The results of this study suggest that thermal pleasure not only increases during transients, but also by a long-term mode. We call this "seasonal alliesthesia". In contrast to the temporal alliesthesia, which occurs with a stimulus towards neutrality directly after exposure to non-neutral conditions, seasonal alliesthesia is grounded on the long-term experiences, that in summer warm thermal conditions prevail and that cool conditions are more likely leading to neutrality and perceptions of pleasure.

Despite the decreased number of adaptive opportunities, further limitations of this study arise from the number of subjects and that the situation (work place), geographical, and cultural circumstances were fixed. Therefore, this study needs to be repeated in other contexts and with a larger number of subjects before the results can be generalized.

Despite revealing differences in the effect of adaptation and alliesthesia, the findings open a much broader discussion to be conducted within the scientific community as well as between the scientific community, practitioners, and clients. This discussion evolves out of the results that – depending on the dimension of thermal comfort used, i.e. thermal sensation or thermal pleasure – the then so-called "optimal" conditions vary. The "optimal" conditions based on the dimension of thermal sensation together with the common assumption, that neutral conditions must be favoured, leads to the demand of thermal conditions around a PMV of 0 (see Figure 1 and Figure 2). The dimension of thermal pleasure suggests distinct thermal conditions to be favoured depending on sex and season (see Figure 3): the “optimal” conditions based on the highest degree of thermal pleasure vary according to the data of this experiment between conditions with a PMV of +0.8 (for females in winter) and -0.9 (for males in summer).

De Dear, Brager, and Cooper (1997) describe the differences in the relationship between thermal sensation and preference found in previous studies as “semantic discrepancy” or “semantic artefacts” attributable to different conceptions of people related to the labels of “warm” or “cold” depending on their overall situation (see Schakib-Ekbatan, Becker, and Schweiker (n.d.) for a qualitative approach to these difference). The distinction between sensation and pleasure described above stated that one is a measure of perceived intensity, the other a measure of perceived positive or negative feelings (like or dislike). In addition, it should be noted that a judgement of optimal conditions based on thermal sensation requires an additional assumption regarding the range of intensity to be considered as optimal. The classic assumption is a vote between “slightly cool” (-1) and “slightly warm” (+1). The results of this paper as well as previous results (Fuchs et al., 2018; McIntyre, 1978) suggest that this assumption needs to be revisited or other dimensions such as thermal pleasure taken as more valid dimensions of thermal comfort.

The outcome of such discussion has direct implications on other aspects such as the energy demand of buildings and the type of HVAC system, so that the discussion needs to be very careful. On the one hand, the adaptive concept suggests minor differences between males and females, warmer conditions acceptable in summer, and cooler conditions in winter. On the other hand, the concept of alliesthesia suggests rather significant differences between males and females, cooler conditions in summer and warmer in winter to be preferred. At the same time, permanently cool conditions in summer could likely revers the seasonal alliesthesial effect due to people then gaining the long-term experience that in summer warm conditions lead towards neutrality and a high level of pleasure. The consequences for the operation of buildings is a challenging discussion to be continued with future research work.

5. References

ASHRAE, 2004. Standard 55-2004, Thermal environmental conditions for human occupancy. *American Society of Heating, Refrigerating and Air-Conditioning Engineering, Atlanta, USA*.

Auliciems, A., 1981. Towards a psychophysiological model of thermal perception. *International Journal of Biometeorology*, 25, pp.109–122.

Bates, D., Mächler, M., Bolker, B. and Walker, S., 2014. Fitting Linear Mixed-Effects Models using lme4. *arXiv:1406.5823 [stat]*.

Cabanac, M., 1971. Physiological role of pleasure. *Science*, 173(4002), pp.1103–1107.

Cabanac, M., 1992. What is sensation? In: R. Wong, ed., *Biological Perspectives on Motivated Activities*. Ablex, Northwoord, NJ.

de Dear, R.J., 2011. Revisiting an old hypothesis of human thermal perception: alliesthesia. *Building Research & Information*, 39(2), pp.108–117.

de Dear, R.J., Brager, G.S. and Cooper, D., 1997. Developing an Adaptive Model of Thermal Comfort and Preference. In: *Final Report on ASHRAE Research Project 884. Macquarie University Sydney*.

Fanger, P.O., 1970. *Thermal Comfort Analysis and Applications in Environmental Engineering*. McGraw-Hill, New York.

Fuchs, X., Becker, S., Schakib-Ekbatan, K. and Schweiker, M., 2018. Subgroups holding different conceptions of scales rate room temperatures differently. *Building and Environment*, [online] 128, pp.236–247. Available at: <https://www.sciencedirect.com/science/article/pii/S0360132317305474>.

Heffner, C.L., 2001. Psychology 101. *Online virtual psychology classroom, AllPsych and Haffner Media Group Inc., Downloaded on October*, 22, p.2014.

Hori, S., 1995. Adaptation to heat. *Japanese Journal of Physiology*, 45, pp.921–946.

Humphreys, M., 1978. Outdoor temperatures and comfort indoors. *Batiment International, Building Research* *and Practice*, 6(2), p.92.

Humphreys, M.A., 1976. Field studies of thermal comfort compared and applied. *Journal of the Institution of Heating and Ventilating Engineers*, 44, pp.5–27.

Humphreys, M.A. and Nicol, F., 1998. Understanding the Adaptive Approach to Thermal Comfort. *ASHRAE Transactions*, 104 (1), pp.991–1004.

ISO 7730, 2005. *Ergonomics of the thermal environment: analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*.

ISO 9886, 2004. *Ergonomics–evaluation of thermal strain by physiological measurements*. *Geneva: International Organisation for Standardisation*.

Kingma, B.R. and van Marken Lichtenbelt, W.D., 2015. Energy consumption in buildings and female thermal demand. *Nature Clim. Change*, [online] 5(12), pp.1054–1056.

van der Lans, A.A., Hoeks, J., Brans, B., Vijgen, G.H., Visser, M.G., Vosselman, M.J., Hansen, J., Jorgensen, J.A., Wu, J., Mottaghy, F.M., Schrauwen, P. and van Marken Lichtenbelt, W.D., 2013. Cold acclimation recruits human brown fat and iincrease nonshivering thermogenesis. *The Journal of Clinical Investigation*, (123), pp.3395–3403.

McIntyre, D.A., 1978. Seven point scales of warmth. *Building Services Engineering Research and Technology*, 45, pp.215–226.

Van Ooijen, A.M.J., van Marken Lichtenbelt, W.D., Van Steenhoven, A.A. and Westerterp, K.R., 2004. Seasonal changes in metabolic and temperature responses to cold air in humans. *Physiology & behavior*, 82(2), pp.545–553.

Parkinson, T. and de Dear, R., 2016. Thermal pleasure in built environments: spatial alliesthesia from contact heating. *Building Research & Information*, [online] 44(3), pp.248–262. Available at: <https://doi.org/10.1080/09613218.2015.1082334>.

Parkinson, T. and de Dear, R., 2017. Thermal pleasure in built environments: spatial alliesthesia from air movement. *Building Research & Information*, [online] 45(3), pp.320–335. Available at: <https://doi.org/10.1080/09613218.2016.1140932>.

Parkinson, T., de Dear, R. and Candido, C., 2016. Thermal pleasure in built environments: alliesthesia in different thermoregulatory zones. *Building Research & Information*, [online] 44(1), pp.20–33. Available at: <https://doi.org/10.1080/09613218.2015.1059653>.

Parkinson, T. and de Dear, R.J., 2015. Thermal pleasure in built environments: physiology of alliesthesia. *Building Research & Information*, 43(3), pp.288–301.

R Development Core Team, 2012. *R: A Language and Environment for Statistical Computing*. [online] Vienna, Austria: R Foundation for Statistical Computing, Vienna, Austria. Available at: <http://www.r-project.org>.

Schakib-Ekbatan, K., Becker, S. and Schweiker, M., n.d. To be decided. In: *Rethinking Thermal Comfort. Windsor conference*.

Schweiker, M., 2016. comf: An R Package for Thermal Comfort Studies. *The R Journal*, [online] 8(2), pp.341–351. Available at: <https://journal.r-project.org/archive/2016/RJ-2016-050/RJ-2016-050.pdf>.

Schweiker, M., Fuchs, X., Becker, S., Shukuya, M., Dovjak, M., Hawighorst, M. and Kolarik, J., 2017. Challenging the assumptions for thermal sensation scales. *Building Research & Information*, 45(5), pp.572–589.

Zhang, H., Arens, E., Huizenga, C. and Han, T., 2010. Thermal sensation and comfort models for non-uniform and transient environments, part II: Local comfort of individual body parts. *Building and Environment*, [online] 45(2), pp.389–398.

Windsor Conference
Rethinking comfort
12th - 15th April 2018

Performance of medium-rise, thermally lightweight apartment buildings during a heat wave

Ella S. Quigley[1] and Kevin J. Lomas[1]

[1]Building Energy Research Group, School of Architecture, Building and Civil Engineering, Loughborough University, UK. K.j.lomas@lboro.ac.uk

Abstract: There is growing evidence that medium rise, thermally lightweight, well insulated, naturally ventilated, single aspect block of flats are at risk of overheating especially when sited in the SE of England. This paper reports the thermal comfort and heat stress conditions recorded in 15 flats located in North London on the outer fringes of the urban heat island. The flats were built using off site, light gauge steel prefabrication methods. Bedrooms on floors one and two and on floors seven to eleven were monitored for 22 days during July and August 2013, a period that included a heat wave, which precipitated a level 3 heat wave alert. The risk of overheating was assessed using the static CIBSE Guide A criteria and the three CIBSE TM52 adaptive thermal comfort criteria. Heat stress levels in one room were assessed using the Humidex and Heat Index metrics. The bedrooms on floors one and two did not overheat whereas all flats on the upper floors failed both the static and the adaptive criteria. Four of these flats were chronically and severely overheated, producing conditions that would lead to heat stress. The results strongly suggest that the design, ventilation and servicing strategy, combined with the inherent fragility of thermally light weight and well insulated construction, is inappropriate in some areas of the UK and may even be dangerous in hot summers. The findings have significance for construction companies, landlords and social housing providers and those concerned with construction guidelines and the building regulations.

Keywords: Apartment buildings, modern methods of construction, overheating, heatwave, measurement

1. Introduction

Homes from the south of England to the north of Scotland are at risk of overheating during the summertime (Bezaiee et al, 2013; Lomas and Porritt, 2017). Excess heat affects the health and wellbeing of occupants, especially if sleep is degraded. In extremis, the heat stress caused can lead to premature mortality, especially amongst more vulnerable members of society (PHE, 2015). As the climate warms and heat waves become more frequent and severe the problem will become ever more pressing, heat-related deaths could treble by 2050 if action is not taken (ZCH, 2015). The UK Committee on Climate Change Adaptation Sub-Committee (CCC) tells on the UK government that '*more action is needed*' to reduce the risks to health and well-being (CCC, 2014; CCC, 2017).

New dwellings are particularly vulnerable and flats and apartment buildings can suffer from chronic overheating (McLeod and Swainson, 2017). A number of factors combine to create the problem. The potential to ventilate adequately is restricted due to limited operable window areas, external noise and pollution, and geometries that preclude cross ventilation. Expanding urban areas create heat islands, which generate elevated temperatures curtailing night time ventilation cooling. The need to prevent winter heat loss, reduce heating energy demands and so reduce greenhouse gas emissions results in increasing levels of insulation. There is also greater use of thermally lightweight construction techniques, which speed construction and may improve buildings' thermal integrity, and a desire to simplify designs and reduce costs, which militates against for example, external shading. So-called modern methods of construction, in which elements of the building, or whole rooms, are constructed off site exemplify this approach. Finally, apartments are becoming smaller, with lower ceilings, which results in higher internal heat gain from occupants and appliances and from the hot water distribution pipework (Lomas and Porritt, 2017).

The risk of overheating in UK apartments and flats is a well-known industry problem (ZCH, 2015; GHA, 2014) and has been a concern for the UK government for some time (DCLG, 2012), however, the problem remains largely unreported in open literature. This paper reports a monitoring study that provides evidence of the extent and severity of overheating in a medium rise apartment block in north London, UK.

2. Description of building

2.1. Case study details

The apartment building designed as student accommodation is located in north London. It comprises two blocks, Block A has seven storeys and Block B has 12 storeys, but steps down in height to the west end, such that the 12th floor is approximately two thirds the area of the ground floor (Fig.1.).

Figure 1: Plan of the buildings (left) and images showing Block A and Block B from within the courtyard (centre) and Block B from the north-west (right) (Images from Google Maps, 2014)

Table 1: Description of building, Block B

Feature	Description
Location	North London
Year constructed	2011-2012
Building use	Student hall of residence
Building occupancy	355 days per year
Number of storeys	Up to 12
Number of flats	55
Number of occupants	529
Flat size	Mix of 3, 5, 7, 9 and 10 bedroom flats (mainly larger flats)
Construction system	Bedrooms, some kitchens - light-gauge, steel modular system. Ground floor, stair cores and some kitchens – reinforced precast concrete.
External facade	Rendered and clad rigid insulation, flat roof
Fenestration	Double glazed, aluminium frames
Space heating	Hydronic radiators supplied from a community CHP plant
Ventilation	Centralised extract systems in flats with outlets in en-suite shower rooms, kitchen and hall. Window opening restricted to 150mm from frame.
Solar shading	Internal blinds, slightly recessed windows in places

The majority of monitored bedrooms were in the east and west parts of the building, only one room faced south, and none faced north. The east facing flats on the lower floors are shaded from the morning sun by Block A.

The two blocks are predominantly formed of room modules made off-site using light gauge-steel as the primary structural component. Timber board and plasterboard assisted with lateral racking rigidity, with insulation placed between the steel elements to control heat loss. Parts of the building were constructed from steel reinforced precast concrete beams, columns and panels including: the ground floors, stair cores, the majority of kitchens and six bedrooms in Block B (Table 1). Non-modular components were used for the external cladding and other structural purposes.

Each flat comprises a corridor, kitchen and from three to ten ensuite bedrooms (average of 9.6 bedrooms per flat). The bedrooms in each flat have a single aspect facing either north, east, south or west, kitchens have either one or two aspects. The corridors run down the centre of the blocks with the stair core at one end and the kitchen at the other, with bedrooms in between (Fig. 2).

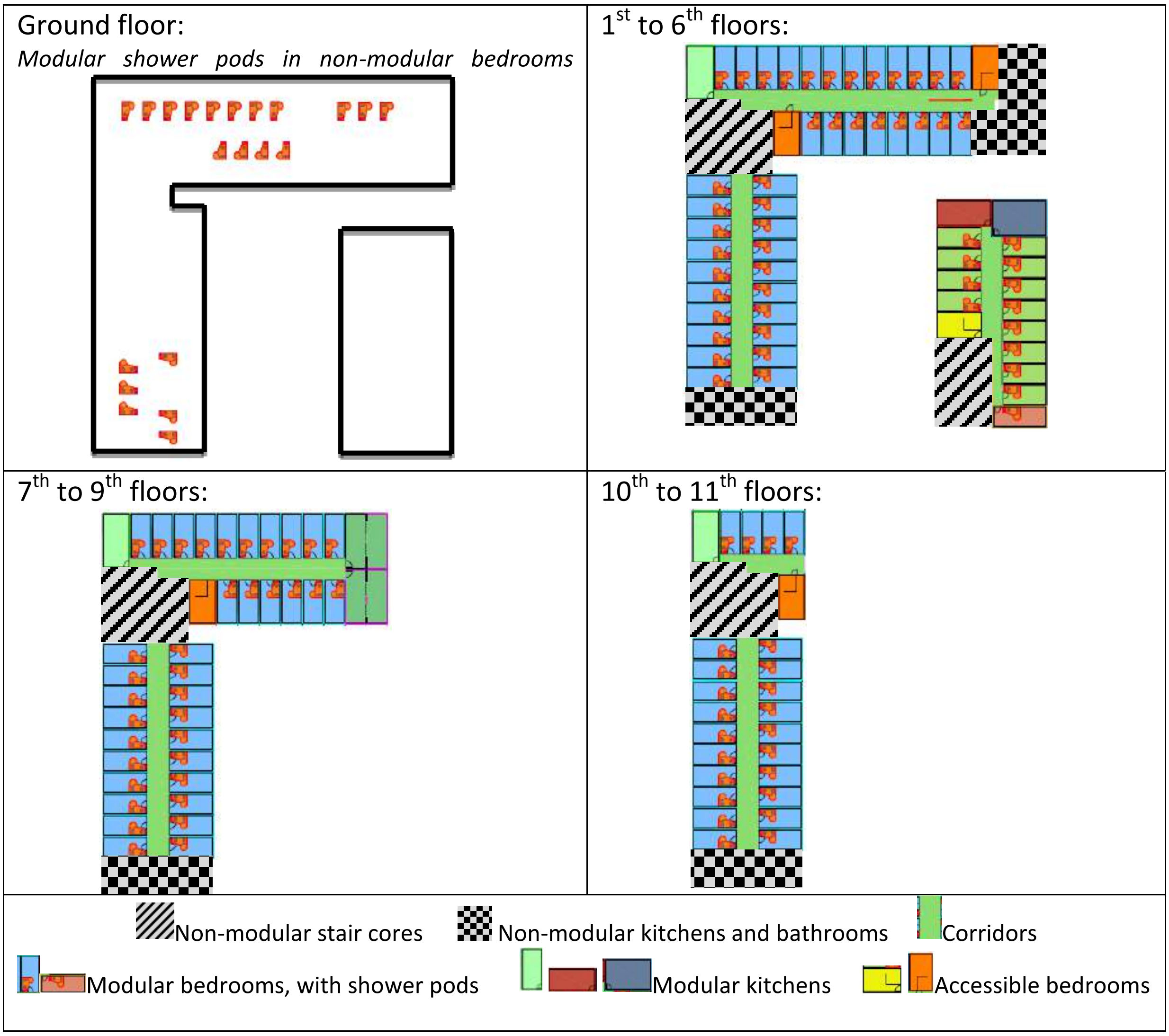


Figure 2: Floor layouts highlighting modular and non-modular components

The external facade was fitted on site and comprises rigid insulation fixed to the modules with various types of render and cladding (Fig. 3). A white or grey render system is used on all facades of both blocks. Various types of rain screen cladding are used across the entire ground floor and on all facades that face away from the courtyard. Some individual modular rooms have three or four different types of facade material attached to their external wall, but the majority have one or two (typically the white and/or grey render systems).

Four thicknesses of rigid insulation were used, resulting in a variable wall thickness across the facade, the thickness of rigid insulation is linked to the facade materials used (Fig. 3). Nothing was known about the thermal properties of the facade materials, or the impacts that using differing facade materials and insulation thicknesses had on the U-value of different sections of wall.

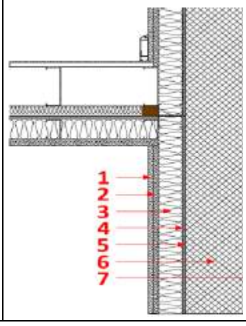
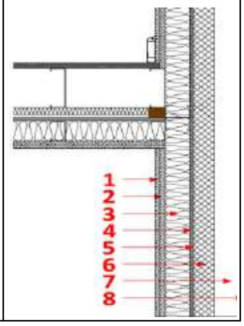
Components	Designs 1, 2 & 3	Design 4
1. 15mm Plasterboard 2. 15mm Plasterboard with foil backed VCL 3. 75mm steel stud wall with 60mm Rockwool 4. 10mm racking board 5. 2mm breather membrane 6. Designs 1, 2 and 3: 100, 150 or 200mm rigid insulation with low-e VCL facing 7. Designs 1,2 and 3 External render, Designs 4 90mm air cavity 8. Design 4 Cladding		

Figure 3: Different external facade designs for the London case study building

The buildings contain 21 different styles of windows plus curtain walling on the ground floor, the style of glazing used varies depending on the type of room and location in the building. The windows in bedrooms and kitchens are double-glazed with top hung openings that were fitted in the factory to the external face of the modules (Fig. 4A). Due to the variable thickness of the external walls, some windows are recessed within the facade (Fig. 4B) and some are not. Opening is restricted to 150mm horizontally from the window frame so windows in walls with 200mm of rigid insulation barely open past the facade (Fig. 4C).

The stair cores have fixed opaque windows on the external facade, however they do not penetrate into the stair cores (Fig. 4D), the only function seems to be to provide the external appearance of windows. The original architect's drawings showed louvered panels which would have enabled ventilation of the stairwells; but the constructed building features the fake windows in their place.

A B C D

Figure 4: Window in bedroom module, not recessed in facade (A), Bedroom window recessed in facade showing the extent of window opening (B), Bedroom window in planar facade– extent of window opening (C), Stair core, fixed, opaque windows with large bedroom windows left & right (D)

Space heating and hot water are provided by a CHP plant that supplies the whole site; it is believed to use biomass fuel. Heat from the CHP plant is transferred to the building via a heat exchanger in Block B and the hot water then pumped around the building. All the building services are routed up through the building from the plant and switch rooms on the ground floors via the stair cores. There are back up boilers and communications rooms located throughout the stair cores. Services are then routed along the corridors to each of the flats.

Each bedroom and kitchen has a radiator, rated at 807 watts and 1417 watts respectively. Thermostatic radiator valves (TRVs) on each radiator are the only means of occupant control. Space heating is available whenever the external temperature is below 15°C, which is measured by an external temperature sensor connected to the BMS system.

Each flat has its own ventilation system, centrally powered from the kitchen. Air is extracted via the cooker hood in kitchens, and vents in the en-suite in bedrooms and the flat corridors. It is not clear if there is any inlet ducting.

3. Monitoring

An EnOcean-enabled wireless sensor network (WSNs) was set up to monitor internal air temperature, relative humidity and window opening. The network comprised a network controller, sensors and repeaters to capture data from temperature and relative humidity sensors fixed to bedroom walls away from direct solar radiation and heat sources. In addition, standalone MadgeTech temperature sensors were fixed to the radiators in each room. The intention was to identify the use of heat emitters, but during the monitoring period no heat was available and the radiators were definitely not used (Table 2).

Problems with the reception of data from the WSN, thought to be caused by signal shielding, meant that the only reliable wireless data was temperature and humidity data from room 10Wa. It was discover however that the temperature sensors fixed to the radiators provided reliable measures of the room temperature, providing very similar values to those recorded by the wall- mounted sensor (Fig 5); temperature recorded by these sensors are reported throughout this work.

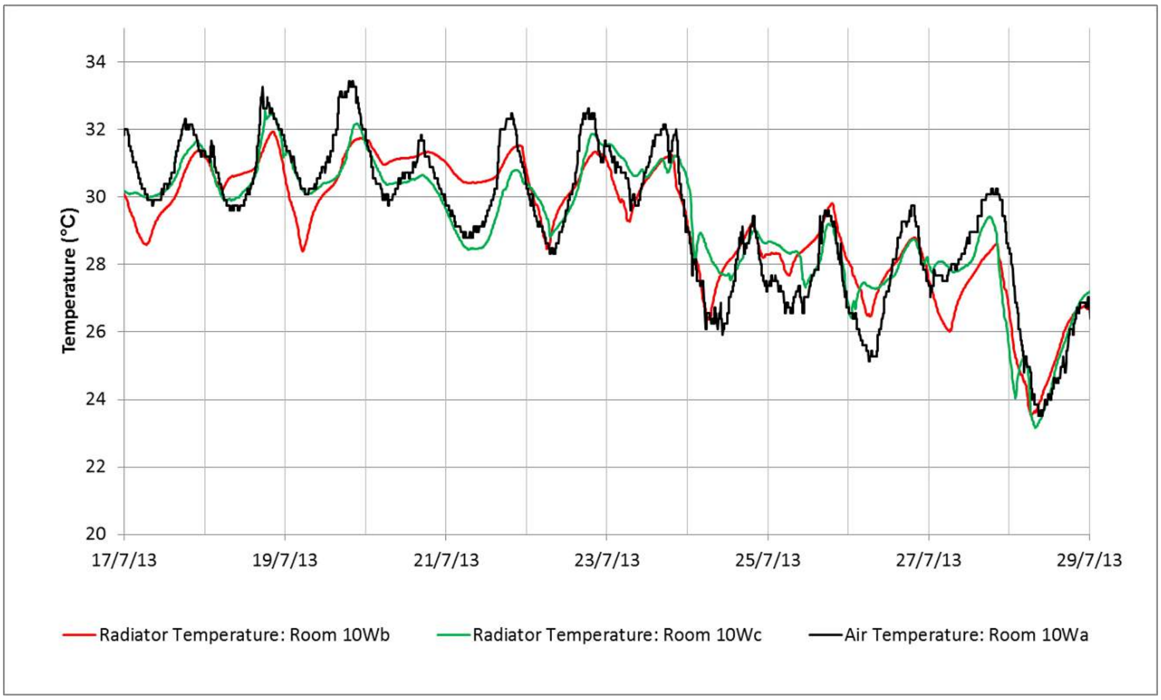


Figure 5: Comparison of air temperature and radiator temperature data

Table 2: Monitoring equipment used in case study building [EnOcean Alliance, 2014; MadgeTech, 2014]

Equipment	Specifications
Smart Building Ltd temperature and relative humidity sensor 	Solar powered Temperature measurement: 0°C – 40°C Relative humidity measurement range: 0% – 100% Temperature measurement accuracy: ±0.5°C Relative humidity measurement accuracy: ±5%
MadgeTech 101A standalone temperature sensors 	Battery powered Temperature measurement range: -40°C to 80°C Temperature measurement accuracy: ±0.5°C Logging capacity: 1 million readings

4. Overheating and heat stress metrics

To determine the occurrence and severity of overheating, the temperature data were analysed using static (CIBSE, 2006) and adaptive (CIBSE, 2013) overheating metrics. The heat stress due to the combined effects of temperatures and humidity in room 10Wa was analysed using heat stress metrics, Humidex (Humidex, 2015) and the Heat Index (Heat Index, 2015).

Both the static and adaptive criteria are applicable to occupied hours with the former applying to the whole year and the latter to the summer period (May to September inclusive). Of course, in monitoring studies, it is not always possible to monitor for these lengths of time and it is not always possible to be confident about when rooms are, or are not occupied. In this work, the criteria are applied only to the data from the monitoring period assuming that the apartments, which are student accommodation, could be occupied at any time. Many previous monitoring studies have adopted the same approach.

The static overheating criteria were taken from CIBSE Guide A (CIBSE, 2006), where overheating is deemed to occur if the measure operative temperatures:

- in bedrooms exceeds 26°C for more than 1% of occupied hours per year; and
- in living areas exceeds 28°C for more than 1% of occupied hours per year.

In this research the percentage of hours during the monitoring period that the measured temperature exceed these criteria is reported along with an estimate of the percentage of hours that would exceed the limiting values if there were no more hours of overheating during the whole summer.

Static criteria have been criticised in recent times because they do not take into account the extremity or duration of overheating, or people's ability to adapt to a changing climate (CIBSE, 2013). The recently published CIBSE Technical Memorandum 59 (CIBSE, 2017) retains the static criterion for bedrooms but neither TM59 or the most recent CIBSE Guide A (CIBSE, 2015) use the living room criterion. However, by retaining the use of this criterion here, it is possible to compare our results with those form earlier monitoring studies.

The adaptive overheating criteria were taken from CIBSE Technical Memorandum 52 (CIBSE, 2013), which takes at the upper operative temperature threshold (T_{upp}) and the lower threshold (T_{min}) to be the Cat II envelope as defined in BSEN15251 (BSI, 2007). The thermal comfort thresholds increase with the running mean of the ambient temperature and Cat II applies to normal health people, which is appropriate for the occupants of the monitored flats. Three criteria are used to determine the extent and severity of overheating and a building is deemed to overheat if it failure of two or more criteria.

Criterion 1: The operative temperature should not exceed T_{max} by more than 1K for more than 1% of occupied hours.

Criterion2: The daily weighted operative temperature, $W_{e,}$ should not exceed $6^oC.h$.

Criterion3: The upper threshold T_{max} should never be exceeded by 4K, T_{upp}.

In this research, for Criterion 1, the percentage of hours that exceed T_{max}+1K is calculated. For Criterion 2, a value of $1^oC.h$ was recorded if T_{max} was exceeded by 1K in a given hour, 3.2 °C.h if it was exceeded by 3.2K, etc. The total °C.h, W_e, for each day in the monitoring period was then compared with the limiting value of 6°C.h. The maximum daily value is reported along with the number of days on which the limiting value was exceeded. For Criterion 3 the number of days that exceeded T_{upp} (T_{max}+4K) is also reported.

Heat stress was calculated for room 10Wa using two metrics, which combined the effects of humidity and temperature. The Canadian Humidex index is used by meteorologists and reported in weather forecasts, and can be used to indicate when workplace conditions are uncomfortable or dangerous. The Humidex value is calculated using:

$$H = T_{air} + 0.5555 * (6.11 * \exp(5417.753 * (1/273.16 - 1/(T_{dp} + 273.16))) - 10)$$

Where H = Humidex index (^oC);
T_{air} = measured air temperature (°C); and
T_{dp} = dew point temperature (°C).

The degree of discomfort or heat stress is then expressed as shown in Table 3.

Table 3: Humidex heat stress scale

Humidex index, H/ ^oC	**Degree of discomfort**
H<30	No discomfort
30≤H<40	Some discomfort
40≤H<45	Great discomfort: avoid exertion
45≤H<54	Dangerous
H>54	Heat stroke imminent

In this research, the dew point temperature was calculated from the measured hourly relative humidity and temperature values, and the variation of the Humidex value over the monitoring period calculated.

The Heat Index, which is used in the USA in weather forecasts, can also be used for workplace assessment. The Heat Index (HI), where temperature is in Fahrenheit, is given by:

$$HI_1 = 0.5 * \left(T_{air} + 61 + \left((T_{air} - 68) * 1.2\right) + (RH * 0.094)\right) \quad \text{If} \quad \frac{(HI_1 + T_{air})}{2} < 80°\text{F}$$

Otherwise:

$$HI_2 = -42.379 + 2.04901523 * T_{air} + 10.14333127 * RH - 0.22475541 * T_{air} * RH - 0.00683783 * T^2 - 0.05481717 * RH^2 + 0.01228774 * T^2 * RH + 0.00085282 * T * RH^2 - 0.0000199 * T^2 * RH^2$$

Where: T_{air} = Air temperature (^{o}F); and

RH= measured relative humidity (%).

Adjustments have to be made to these equations for very high and very low relative humidity, but they were not needed for this research. The degree of discomfort or heat stress is then expressed as shown in Table 4.

Table 4: Heat Index heat stress scale

Heat Index / °F	Heat Index / °C	Category
80≤HI<90	26.7≤HI<32.2	Caution
90≤HI<105	32.2≤HI<40.6	Extreme caution
105≤HI<130	40.6≤HI<54.4	Danger
HI>130	HI>54.4	Extreme danger

5. Prevailing weather conditions

During the summer of 2013, the months of May and June were cooler in the SE of England than the 30-year average. However, in July and August when the monitoring took place the temperatures were higher than the 30-year average. In fact, July 2013 was the third warmest July in the region since records began in 1910 (UK Met Office 2014a).

The UK Met Office deemed that the heatwave of July 2013 lasted from 6th to 24th July, but was not particularly extreme. Over these 19 days, a daily maximum temperature of at least 28°C was measured at one or more locations in the UK, with a maximum temperature of 33.5°C recorded at Heathrow and Northolt on 22nd July.

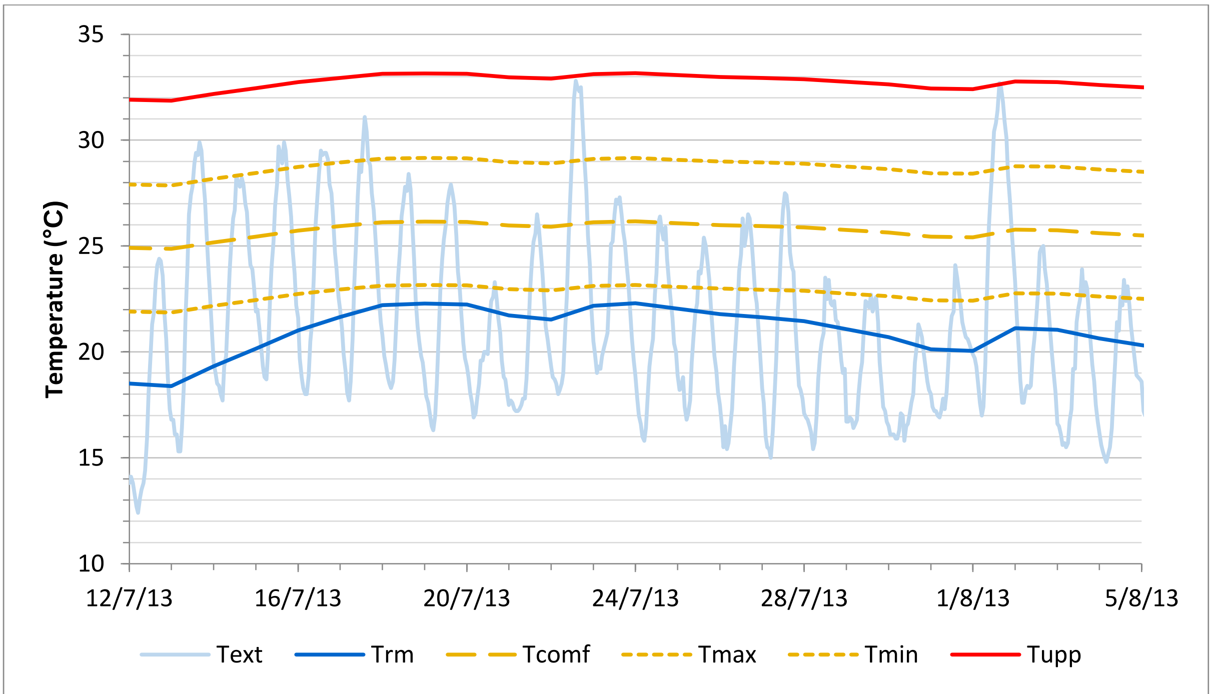


Figure 6: Ambient temperature recorded at St James' Park in London between 12th July – 4th August 2013, the running mean of the ambient temperature (Trm), the Cat II adaptive thermal comfort thresholds (Tmax and Tmin) and the CIBSE TM52 Criterion 3 upper limit temperature (Tup).

The temperature measured at the St James Park weather station in London (UK Met Office, 2014b), which is the source of the temperature data for the work reported here, reached above 28°C for five consecutive days from 13th to 19th July inclusive, with a maximum temperature of 32.8°C on 22nd July (Fig. 6). Based on the World Health organisation's definition of a heat wave, the duration was from 13th to 18th July inclusive (WHO, 2015). On 17th July 2013 Public Health England issued a level 3 heat wave alert for London and the SE (PHE, 2013), which means there is *a '90% chance of heat wave conditions where temperatures are high enough over threshold levels to significant effect on health'* (PHE, 2015)

6. Measured internal temperatures

During the monitoring period, the internal temperatures in the east-facing rooms on the first and second floor were warm but not excessively so, with mean temperatures between 20.2 and 24.2°C and a maximum temperature in room 1Ea of 29.7°C on 1st August (Fig. 7), when the ambient temperature reached almost 33°C. During the period defined by the WHO as a heatwave, 13th to 18th July, all four rooms maintained internal temperatures below the peak outdoor temperatures. On the isolated hot days of 22nd July and 18th July the indoor temperatures were up to 5K below ambient. Throughout the monitoring period indoor temperatures were virtually always between the upper and lower adaptive thermal comfort thresholds. This suggests that the combination of construction, shading and ventilation provision enabled occupants to regulate their thermal environment effectively.

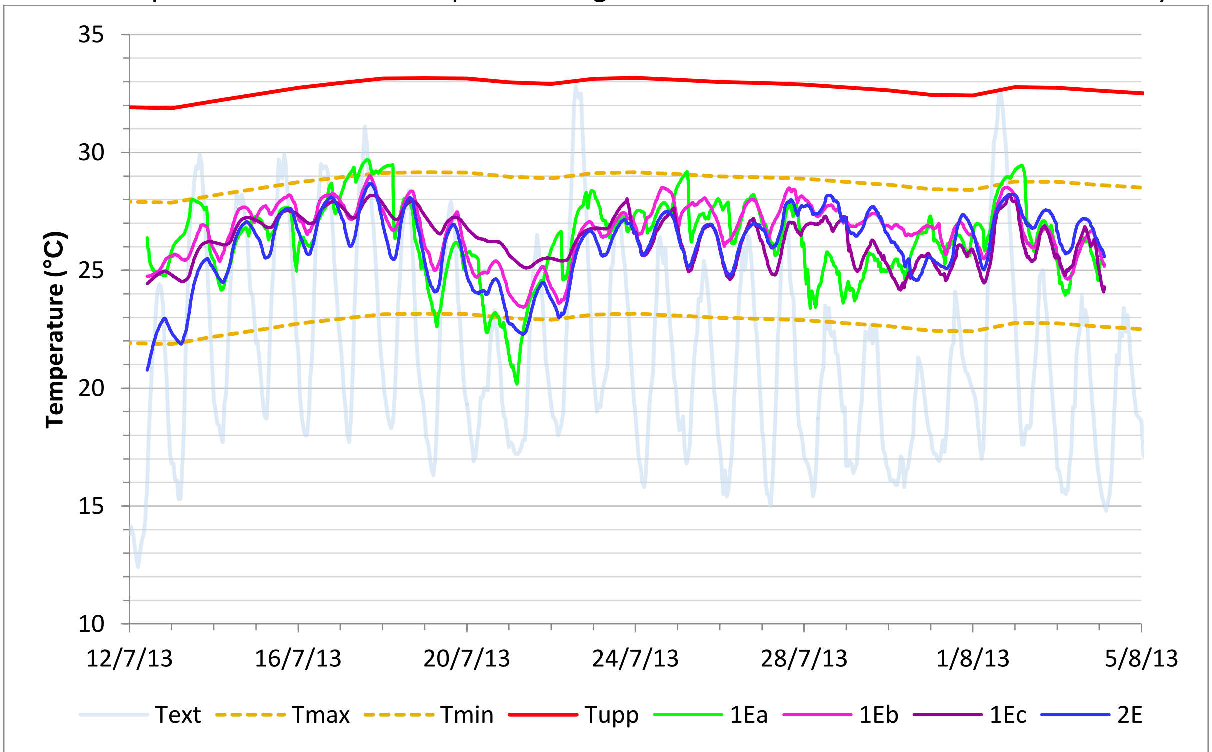


Figure 7: Internal temperatures in rooms on first and second floor between 12th July and 4th August, showing the Cat II adaptive thermal comfort thresholds (Tmax and Tmin) and the CIBSE TM52 Criterion 3 upper limit temperature (Tupp)

The rooms on the upper floors behaved quite differently (Fig. 8). The indoor temperatures were similar to those on the lower floor during the sustained cooler periods, e.g. 28th to 31st July, however, they reacted much more strongly to warmer ambient conditions. For example, between 12th July and 27th July, the indoor temperatures were high, and they stayed high, exceeding the ambient temperature at all times. Even on slightly cooler days, e.g. 18th to 21st July, the indoor temperatures floated well above the ambient temperatures at all times. Consequently, the indoor temperatures frequently exceeded the upper adaptive thermal comfort threshold (T_{upp}). The data suggest that, on the upper floors, the building lacked resilience to elevated temperatures and that the occupants may not have had the adaptive opportunities required to prevent overheating. Nor, it seems could they take retrospective action to bring the temperatures back down even when cooler night time ambient air was available for cooling: at night, e.g. in the early morning of 20th July, the ambient temperature was 15K or more less than the indoor temperature!

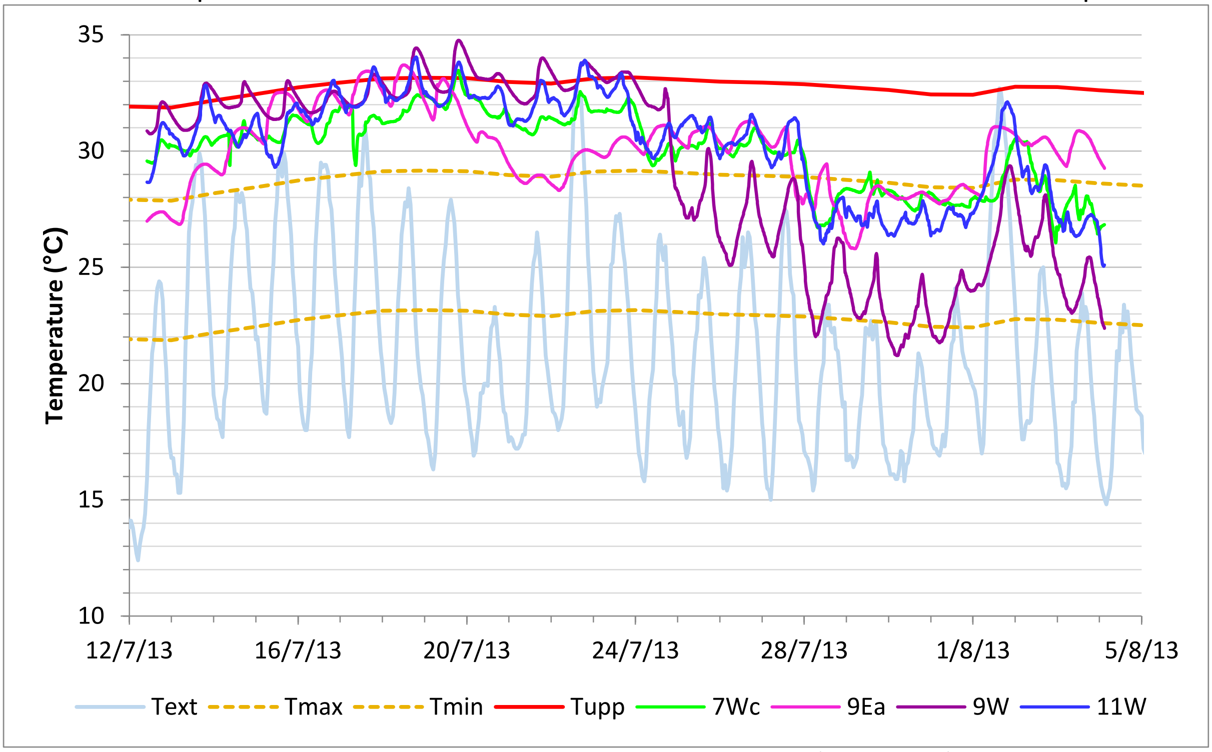


Figure 8: Internal temperatures in rooms on the upper floors between 12th July and 4th August, showing the Cat II adaptive thermal comfort thresholds (Tmax and Tmin) and the CIBSE TM52 Criterion 3 upper limit temperature (Tupp)

7. Overheating Analysis

To quantify the extent, or otherwise, of overheating both the CIBSE static and adaptive criteria were used. No data were collected about the occupancy of the monitored rooms but as student accommodation could theoretically be occupied at any time of the day or night, being both a bedroom and a living area, it was concluded that overheating should be avoided at all times of day.

7.1 Static criteria

Different static criteria apply to the day and night time periods, 28°C/1% of the time and 26°C/1% respectively. The decision of when to split the day into daytime and night time hours proved not critical to the results, using different splits made no significant difference to the findings. The temperature threshold of 26°C was assumed to apply from 22:00 to 08:00 and 28°C during the daytime hours, between 08:00 and 22:00.

The results reveal that all rooms were above the 26°C threshold for a significant proportion of night time hours (Fig. 9 and Table 5). Although room 2E performed the best, with 44.3% of night time hours above 26°C, this is still well in excess of the 1% limit. All other rooms were above 26°C for at least 50% of the time with rooms 7Wc, 9Ea and 11W above

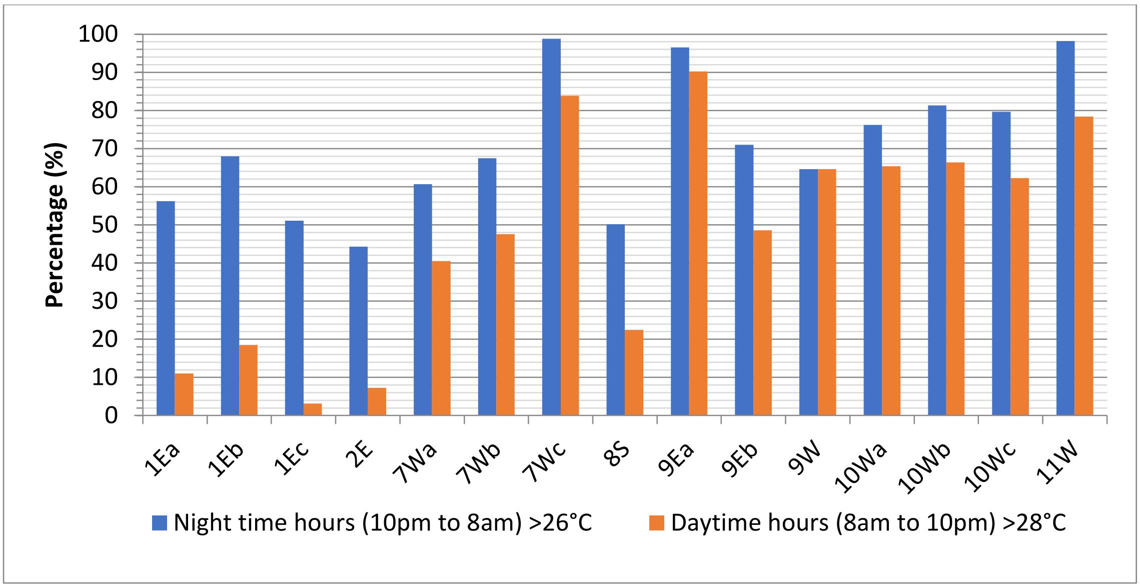


Figure 9: Percentage of the monitored period for which the day and night time temperatures exceeded the CIBSE threshold temperatures of 26°C and 28°C respectively.

for 98.8%, 96.5% and 98.2% of night time hours, respectively.

The rooms exceeded the 28°C threshold during daytime hours for proportionally less time than the night time criterion. However, ten of the rooms exceeded the threshold for at least 40% of the free-running period, with rooms 7Wc, 9Ea and 11W again performing worst. The four rooms on the lower floors, 1Ea, 1Eb, 1Ec and 2E, along with room 8S performed less poorly, but were still well in excess of the 1% criterion.

Table 5: Summary of the recorded room temperatures between 12th July to 4th August and the percentage of day and night time hours above the day and night time static temperature thresholds.

	Temperatures recorded during monitoring period			**Hour exceedance during monitoring period**		**Equivalent annual hours exceedance[1]**	
Room	**Maximum (°C)**	**Minimum (°C)**	**Average (°C)**	**Night time 22:00-08:00 >26°C %**	**Daytime 08:00-22:00 >28°C %**	**Night time 22:00-08:00 >26°C %**	**Daytime 08:00-22:00 >28°C %**
1Ea	29.7	20.2	26.3	56.2	11.0	3.5	0.7
1Eb	29.0	23.4	26.7	67.9	18.5	4.2	1.1
1Ec	28.2	24.2	26.3	51.1	3.2	3.2	0.2
2E	28.7	20.8	26.0	44.3	7.3	2.7	0.5
7Wa	31.1	21.8	26.8	60.7	40.5	3.8	2.5
7Wb	31.4	21.3	27.1	67.5	47.6	4.2	3.0
7Wc	33.5	26.0	30.1	98.8	83.9	6.1	5.2
8S	30.2	21.1	26.2	50.1	22.4	3.1	1.4
9Ea	33.7	25.8	30.1	96.5	90.2	6.0	5.6
9Eb	30.5	23.8	27.5	71.0	48.6	4.4	3.0
9W	34.8	21.2	29.2	64.6	64.6	4.0	4.0
10Wa	33.4	23.2	28.6	76.2	65.4	4.7	4.1
10Wb	31.9	23.3	28.4	81.3	66.3	5.1	4.1
10Wc	32.6	23.2	28.4	79.6	62.3	4.9	3.9
11W	34.0	25.1	30.3	98.2	78.4	6.1	4.9

[1] The monitored period of 543 hours was just 6.2% of the hours in a whole year.
Shaded indicates failing the criterion.

The free-running period spanned 22.7 days, which is only 6.2% of the year. It is salutary to note that even if there were no further hours of overheating in the rest of the year, and the 1% day and night time criteria were deemed to apply to annual hours over 26 and 28°C, all the rooms would still be considered as overheated at night, and all but three overheated during the day.

7.2 Adaptive criteria

The Cat II upper thermal comfort threshold, T_{max}, provides the basis for all three TM52 criteria. During the monitoring period, T_{max} varied from 27.9°C to 29.2°C (Fig. 6), with an average of 28.7°C, which is higher than both the static overheating thresholds.

Criterion 1: The four rooms on the first and second floors never exceeded T_{max} by more than 1K and so all passed TM52 Criterion 1. All the remaining rooms did exceed T_{max} by more than 1K and all for more than 3% of the hours during the monitoring period. As with the static overheating analysis, rooms 7Wc, 9Ea and 11W performed worst, exceeding the threshold 64.7%, 60.8% and 66.2% of the time, respectively (Table 6).

Criterion 2: Because the rooms on floors 1 and 2 never exceeded T_{max} they passed Criterion 2 (Fig. 7). All eleven other rooms, from floor 7 upwards, had weighted exceedances, W_e, greater than 6°C.h on at least four days, with three rooms so overheated that they failed on eighteen days, i.e. c80% of the time. Criterion 2 is designed to indicate the severity of overheating, and with such high weighted exceedances on so many days, it is clear that the rooms on the upper floors were severely and chronically overheating.

Criterion 3: Five of the fifteen rooms failed this criterion, exceeding T_{upp} on one or more occasions between 12th and 23rd of July, (Fig. 8). Room 9W displayed the most severe and most frequent overheating, failing on eleven days; 11W also overheated badly, failing on eight. When these rooms exceeded T_{upp} they did so for between two to twelve hours.

Table 6: Performance of rooms against the CIBSE TM56 criteria during the period 12 July to 4th August 2013 and overall overheating assessment

Room	Criterion 1	Criterion 2		Criterion3		Overall result
	Percentage of hours above upper threshold T_{max} %	Maximum weighted exceedance We **°C**.h	Number of days with We>6**°C**.h -	Maximum exceedance of upper threshold T_{max} K	Number of days where temperature exceeds $T_{upp} = T_{max}+4$ -	Failed two or more Criteria
1Ea	0	5	0	0	0	Pass
1Eb	0	0	0	0	0	Pass
1Ec	0	0	0	0	0	Pass
2E	0	0	0	0	0	Pass
7Wa	5.6	14.7	5	0	0	Fail
7Wb	12.0	30.8	8	0	0	Fail
7Wc	64.7	77.8	18	4.4	1	Fail
8S	3.6	13.0	4	0	0	Fail
9Ea	60.8	90.3	18	4.6	3	Fail
9Eb	6.1	23.2	4	0	0	Fail
9W	54.8	104.0	13	5.6	11	Fail
10Wa	41.8	62.0	14	4.3	2	Fail
10Wb	32.8	49.2	12	0	0	Fail
10Wc	25.6	46.3	10	0	0	Fail
11W	66.2	87.0	18	5.0	8	Fail

Shaded indicates failing the criterion.

Overall assessment: Only the rooms on the first and second floors passed all three criteria and so would be deemed free of overheating risk. In contrast, the eleven rooms on floors 7 and above failed two or more criteria. Five rooms, 7Wc, 9Ea, 9W, 10Wa and 11W, were severely and chronically overheated and failed all three criteria.

7.3 Heat Stress

The conditions were so severe in room 10Wa that, on the Humidex scale, they would have caused '*some discomfort*' (30°C≤H<40°C) for most of the monitoring period with short periods of '*great discomfort*' (40°C≤H<45°C) (Fig. 10).

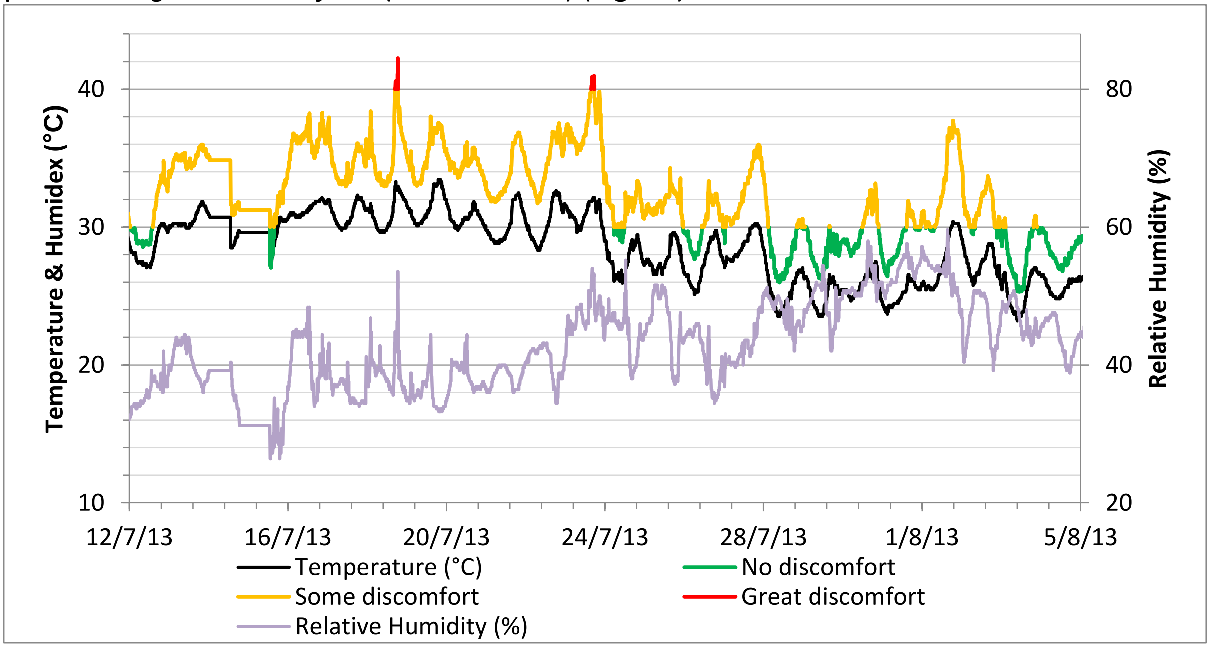


Figure 10: Humdiex rating and measured temperature and relative humidity for room 10Wa between 12th July to 4th August

On the Humidity Index scale, *caution* would be advised (26.7≤HI<32.2°C) for much of the monitoring period with short periods of '*extreme caution*' (32.2≤HI<40.6°C) (Fig 11). This suggests that heat stress would be likely when undertaking moderate levels of activity or, if exposure is prolonged, which it is in this flat, and the others with similar temperatures.

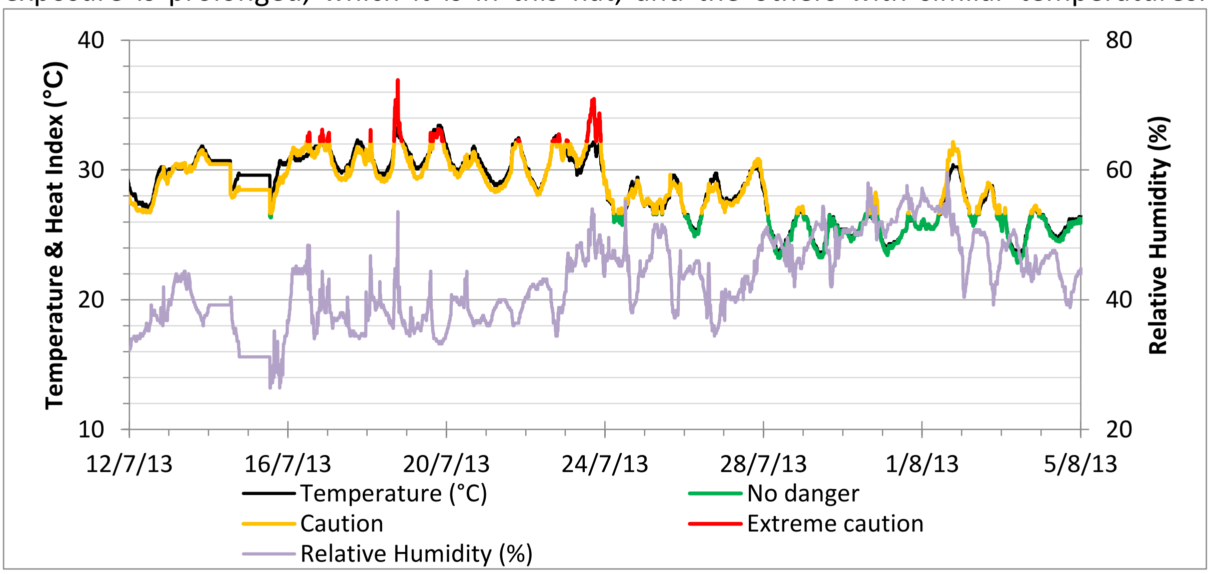


Figure 11: Heat Index rating and measured temperature and relative humidity for room 10Wa between 12th July to 4th August

8. Discussion

The building chosen for this case study was selected to be emblematic of a type that has raised concern about overheating within the building research and construction community. That is, thermally lightweight, medium rise apartment blocks located in the SE of England. The building was in its first year of operation to there was no prior knowledge of its likely summertime performance. The monitoring period, the summer of 2013, included a heat wave so it was possible to see how the building would respond under conditions that will become typical as the UK climate warms.

The rooms on all floors significantly exceeded the CIBSE 26^{o}C/1% night time overheating criterion suggesting that all occupants of this building may suffer from disrupted sleep for many nights successively. Whilst the rooms on the lower floors did not overheat as indicated by the TM52 criteria, those on floor seven and above did. Five rooms were chronically and severely overheated which could render them effectively uninhabitable. Heat stress conditions were monitored in one room, but others in which humidity was not measured, had similar temperatures; the upper parts of the building might also therefore, be damaging to health.

In addition to the intrinsic thermal fragility of the construction form used, other factors conspired to create the severe overheating risk. There was no external shading or any other form of purposefully designed overheating reduction features. The results from the rooms on floor nine do show that the temperatures in the room on the east-facing and site-shaded aspect are substantially lower than in the other rooms.

The only form of adaptive action that the occupants might have taken was to increase the natural ventilation afforded by operable windows. This was inherently limited by the single-aspect design of the rooms, but was also severely curtailed by the restriction of window opening to 150mm which, given the external insulation of 100 to 200mm, meant the free area for ventilation was very limited indeed. In essence therefore there is nothing the occupants can do to escape the heat except to leave their room and possible the building.

Internal heat generation was also a factor. As well as the density of heat gain from occupants and their electrical equipment, heat from the hot water services leaked into the stairwells and corridors and rose up the building. Spot measurements taken off the building's management system during a site visit in November 2012 indicated stair well temperatures varying form 15^{o}C on the ground floor up to 27^{o}C on the top floor. The corridors had no direct connection to the outdoors and so heat could not be ventilated away. In fact, the original drawings showed windows to the stair core, but these had been omitted in the final building and replaced by fixed window-imitating panels. An example perhaps of post design, ad-hoc cost reduction.

The mechanical extracts installed in the flats, which might have exhausted some of the heat, were also ineffective. They were also very noisy and so tended not to be used; the facilities manager reported that some residents had requested their ventilation systems to be turned off. Others have also reported the contribution that cheap, noisy and poorly installed MVHR systems make to overheating risk (Mcleod, 2017).

Whilst there is no doubt that the building had severe overheating problems, it was difficult to fully understand all the causes and this is a weakness of the work. For example, although window opening sensors were installed, because the wireless network did not work it wasn't possible to understand what contribution to cooling, if any, the operable windows were making. Because of privacy and other ethical concerns, it was impossible to know reliably whether rooms were occupied or not. Thus, it wasn't possible to calculate overheating just for the occupied periods and neither was it possible to know if adaptive actions to combat heat could have been taken. Finally, the study did not incorporate a questionnaire survey so the measured temperatures could not be compared with the thermal perceptions of the occupants.

The finding of this work will, it is hoped, provide further ammunition for those in the construction industry, for landlords, social housing providers and tenant groups, and for those concerned with building guidelines and the regulations, who wish to take action to prevent the construction of buildings that overheat. The work will also aid those concerned with the health and well-being of UK citizens. The monitored building is unlikely to be an isolated example. It is just the possibility that the early C21st has seen the construction of a fleet of toxic assets that will be uninhabitable by the mid-century.

9. Conclusions

Temperatures were recorded in a medium rise, thermally lightweight, well insulated, naturally ventilated, single aspect block of flats built using off site construction located in north London UK. The flats were monitored for 22 days during July and August, which included a heat wave that precipitated a level 3 heat wave alert. Temperatures were monitored in flats on the lower two floors and on floors 8 to 11 with relative humidity also recorded in one flat on floor 10.

The risk of overheating was assessed using the static CIBSE Guide A criteria of 26°C/1% for night time hours and 28°C/1% for the daytime. Analysis was also conducted using the CIBSE TM52 adaptive thermal comfort criteria and heat stress was assessed using the Humidex and Heat Index metrics.

The night time temperatures in all the flats had more than 44% of night time hours above 26°C, thereby significantly exceeded the 26°C/1% criterion, suggesting that the sleep of occupants could be seriously disrupted, and for a prolonged period. Whilst the rooms on the lower floors passed the CIBSE TM52 criteria, those on floors 7 and above did not. Four of these flats were seriously overheated with conditions in a 10th floor room that would lead to heat stress.

It appears that the single aspect geometry of the rooms, the well-insulated and thermally light weight construction and the lack of external shading, combined with the blind corridors, the accumulation of internally generated heat in the stair wells and corridors, the restrictions of window opening and the curtailment of background mechanical ventilation systems, created a cocktail of factors that led to chronic and severe overheating.

The results support the findings of others, and indicate that this form of construction is dangerous in hot weather and so entirely inappropriate for, potentially many, areas of the UK especially as the climate warms further. The findings have significance for construction companies, landlords and social housing providers and those concerned with building guidelines and the regulations.

10. Acknowledgements

This work was conducted as part of a doctoral research project pursued within the London-Loughborough Centre for Doctoral Research in Energy Demand. The Engineering and Physical Sciences Research Council (EPSRC) funding for the Centre is gratefully acknowledged (Grant EP/H009612/1).

11. References

Beizaee, A., Lomas, K. J., & Firth, S. K. (2013). National survey of summertime temperatures and overheating risk in English homes. Building and Environment, 65, 1–17. doi:10.1016/j.buildenv.2013.03.011

British Standards Institution, 2007. BS EN 15251: 2007: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. London: British Standards Institution.

CCC, 2014. Managing Climate risks to well-being and the economy, Committee on climate change, adaptation sub- committee, Progress Report 2014, 202pp.

CCC, 2017. Progress in Preparing for Climate Change, 2017 Report to Parliament, Committee on Climate Change, Adaptation Sub-Committee, June 2017, 234pp.

CIBSE, 2006. *Guide A: Environmental Design (7th ed.).* (edited by K. Butcher). London: Chartered Institution of Building Services Engineers

CIBSE, 2013. The limits of thermal comfort: avoiding overheating in European buildings, Technical memorandum, TM52, *Chartered Institution of Building Services Engineers,* London.

CIBSE, 2015. Guide A: Environmental Design (8th ed.). *Chartered Institution of Building Services Engineers,* London: CIBSE, 2017. *Design methodology for the assessment of overheating risk in homes*. Technical memorandum TM59, *Chartered Institution of Building Services Engineers*, London.

DCLG 2012. Investigation into overheating in homes, Literature review, AECOM for the Department for Communities and Local Government, 124pp. ISBN: 978-1-4098-3592-9

GHA. (2014). Preventing overheating: investigating and reporting on the scale of overheating in England, including common causes and an overview of remediation techniques. London: Good Homes Alliance. February, 2014.

Heat Index, 2015, *What is the heat index?.* Available at: <http://www.srh.noaa.gov/ama/?n=heatindex accessed June 2015.

Humidex, 2015, *Humidex Rating and Work.* Available at: http://www.ccohs.ca/oshanswers/phys_agents/humidex.html accessed June 2015.

Lomas KJ and Porritt SM, Overheating in buildings: lessons from research. Building Research & Information, 45(1-2), pp 1-18, (2017), ISSN 0961-3218. doi:10.1080/09613218.2017.1256136.

McLeod, R and Swainson, M, 2017. Chronic overheating in low carbon urban developments in a temperate climate. Renewable and Sustainable Energy Reviews, 74, p201-220.

PHE, 2013. Level 3 'heatwave' alert issued for London and the South East, *Public Health England*, Press Release, 17 July 2013 Available at: https://www.gov.uk/government/news/level-3-heatwave-alert-issued-for-london-and- the-south-east accessed 120118.

PHE 2015, Heat Wave Plan for England, Protecting Health and Reducing Harm from Extreme Heat and Heatwaves, Public health England, May 2015, 32 pp.

UK Met Office, 2014a. *Sunny and warm July in 2013.* Available at: http://www.metoffice.gov.uk/news/releases/archive/2013/warm-july-stats accessed 120118.

UK Met Office, 2014b. *UK Meteorological Office. MIDAS Land Surface Stations data (1853-current).* NCAS British Atmospheric Data Centre. Available at: http://badc.nerc.ac.uk/view/badc.nerc.ac.uk_ATOM_dataent_ukmo-midas, accessed 1st May 2014.

ZCH, 2015. Overheating in homes, the big picture, Zero-Carbon Hub, Full report, 96pp, June 2015.

Percentage of commercial buildings showing at least 80% occupant satisfied with their thermal comfort

Caroline Karmann[1,2], Stefano Schiavon[1], Edward Arens[1]

[1] Center for the Built Environment, University of California, Berkeley, CA 94720-1839, USA, ckarmann@gmail.com

[2] ARUP, 13 Fitzroy street, London, W1T 4BQ, United Kingdom, caroline.karmann@arup.com

Abstract: Most thermal comfort standards prescribe that buildings must provide satisfactory thermal comfort to at least 80% of their occupants. To assess how many buildings meet this criterion, we analysed temperature satisfaction votes from 52,980 occupants in 351 office buildings, obtained via a web-based seven-point satisfaction survey over 10 years, mainly in North America. 43% of the occupants are thermally dissatisfied, 19% neutral and 38% satisfied. The percentage of buildings meeting 80% satisfied occupants was only 2% if one considers votes from +1 to +3 ('slightly satisfied to very satisfied') as representing satisfaction, 8% if one includes votes from 0 to +3 ('neutral to very satisfied'), and 33% if one includes votes from -1 to +3 ('slightly dissatisfied to very satisfied' – a seemingly generous criterion suggested in ASHRAE Standard 55). These results are concerning because they suggest that buildings are far from creating thermal environments that their occupants consider satisfactory. This might be due to inability of the large majority of HVAC systems to provide adequately personalized conditioning or control. This paper also discusses the relevance of the 'satisfaction' metric used for long-term building evaluations.

Keywords: Thermal comfort, satisfaction, occupant survey, post-occupancy evaluation.

1. Introduction

Thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ANSI/ASHRAE 2017). This definition, first adopted in 1992, may not be intelligible to all, and the means by which a 'condition of mind' can 'express satisfaction' is potentially unclear. Nevertheless, this definition simplifies the more delicate and culturally loaded notion of 'comfort' (Shove 2004) into the more tangible idea of 'satisfaction'. This definition further provides a path to measure thermal comfort through 'subjective evaluation'. Satisfaction questionnaires have been widely used in post-occupancy evaluations. The two principal thermal comfort models (Fanger's predicted mean vote (PMV) model (Fanger 1970) and the adaptive thermal comfort model (De Dear et al. 1998, Nicol and Humphreys 2002)) can estimate the 'predicted people dissatisfied' (PPD). For both models, the PPD defines an area around an ideal (neutral) condition in order to provide satisfaction to a given percentage of the people, often 80 or 90%.

The rising interest in workplace well-being, the rapid growth in sensing and actuating technologies, and the potential to link occupant comfort with productivity provide a fertile ground to address and rethink thermal comfort in commercial buildings. Over the last couple of years, we have seen new products (e.g. NEST, Comfy) and new building certification programs (e.g. WELL Building Standard (IWBI 2014)) directly tackling thermal comfort with new methods to both assess and address it. Many certification programs (LEED, WELL, GreenMark) give points for a post-occupancy survey. This may lead to an increase in the assessment of thermal comfort in buildings. We can observe that most recent studies and product developments addressing thermal comfort are re-orienting their scope towards occupant-centric approaches. While this innovative environment can be mesmerizing, it may be worth reflecting on our understanding of comfort in the current building stock, and what levels of comfort have been observed over the last decades.

The objective of this paper is to estimate, based on the Center for the Built Environment (CBE)'s Indoor Environmental Quality (IEQ) Survey results, how many buildings fulfil the comfort standards objective of providing satisfactory thermal comfort to at least 80% of their occupants. This paper is also an opportunity to reflect on thermal comfort definitions and assessment method limitations, and to discuss different approaches.

2. Method

2.1. CBE Occupant IEQ survey database

We used the Occupant IEQ survey database to perform our analysis. This web-based survey, administered by CBE at the University of California Berkeley, first asks building occupants a set of basic questions about demographics, followed by nine core categories of IEQ, including thermal comfort (Zagreus et al. 2004). It measures occupant satisfaction in each of the categories using a 7-point Likert scale with answers ranging from +3 ('very satisfied') to -3 ('very dissatisfied') with 0 as the middle option ('neutral') (see Figure 1). The rating applies to 'general' or 'background' conditions as opposed to 'right here right now' conditions. ASHRAE Standard 55-2017 (ANSI/ASHRAE 2017) prescribes the use of this type of 7-point Likert survey for building post-occupancy assessments.

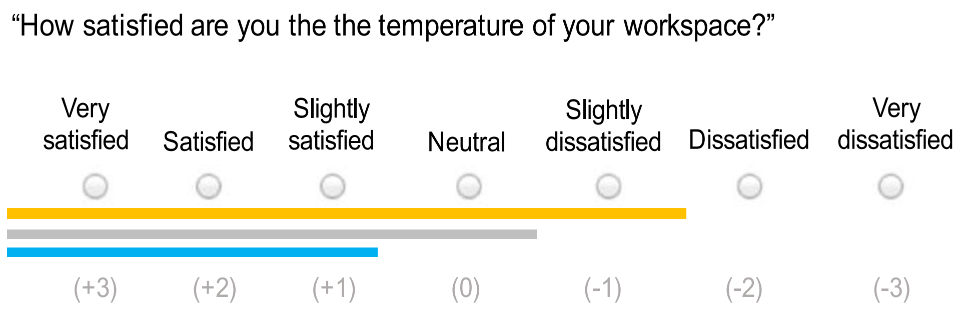


Figure 1: Satisfaction with temperature using a 7-point Likert scale; the coloured lines represent the three satisfaction intervals used in the analysis: "-1 to +3" (gold), "0 to +3" (grey) and "+1 to +3" (blue)

To perform our analysis, we used a subset of the CBE survey database that consists of commercial buildings surveyed up until 2010 and whose building characteristics were verified by our team (Frontczak et al. 2012). Selected buildings were mainly governmental buildings, office buildings occupied by private companies, universities, and research centres. The following buildings were rejected: day care centres and elementary schools, residential buildings, customs office and border stations, airport, museums and libraries, hospitals, sport facilities, buildings in industrial settings (refinery, depot, and warehouse), fire station, and prisons. This subset used for this analysis involves 52,980 occupants in 351 office buildings, mainly in North America. The full description of this dataset is detailed in (Frontczak et al. 2012). For our analysis, we only looked at the results for temperature satisfaction.

2.2. Defining satisfaction

Section 7.4.1 of the current version of ASHRAE Standard 55 (2017) requires the use of a 7-point satisfaction question, and states that for long term evaluation (not 'right-now') it should include votes fall between '-1' ('slightly dissatisfied') and '+3' ('very satisfied') inclusive. This widely inclusive range could be due to the desire to transform satisfaction judgements into acceptability judgements. Yet, in the 2013 version (ANSI/ASHRAE 2013), the standard did not involve the same interval: ratings were restricted to votes between '0' ('neutral) and '+3' ('very satisfied'), and in the 2017 version, in the Informative Appendix L it allows for both options. If we look at the thermal comfort definition, it is also possible to argue that satisfaction should include only ratings explicitly stating a 'satisfied' condition, i.e. from '+1' ('slightly satisfied') to '+3' ('very satisfied'). Based on these observations, we will conduct our analysis for 3 satisfaction intervals: "-1 to +3", "0 to +3" and "+1 to +3".

Per ASHRAE Standard 55-2017 (ANSI/ASHRAE 2017), thermal satisfaction shall be measured with a scale ending with the choices: "very satisfied" and "very dissatisfied". The standard specifies how to calculate the percentage for a given building, by dividing the number of satisfied votes by the total number of votes. This implies that people who did not vote are not counted. The standard does not explicitly provide a target percentage of occupants satisfied for background long-term evaluations.

3. Results

Figure 2 shows the distribution of *occupant* responses for temperature satisfaction. This graph does not consider the difference between buildings but aggregates all individual responses. If we cluster negative and positive votes, we observe that the 43% of the occupants are dissatisfied, 19% are neutral and 38% are satisfied with their thermal environment. This means that the proportion of dissatisfied occupants is higher and that the proportion satisfied. If we assume that an environment is thermally acceptable if we also include 'neutral' and 'slightly dissatisfied' votes, then 'acceptability' would be 57% (from 0 to +3) and to 73% (from -1 to +3).

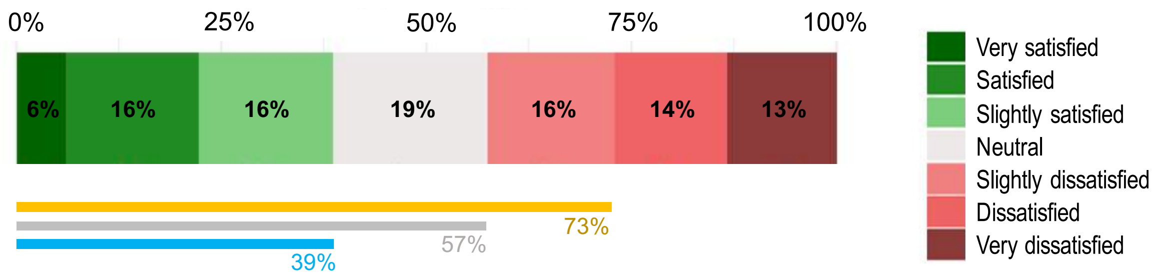


Figure 2: Bar chart showing the distribution of temperature satisfaction votes for 52,980 occupants (in 351 office buildings).

Figure 3 displays the percentage distributions of *buildings* whose occupants meet the three different definitions of temperature satisfaction. On the left side, the results are presented in five bins of satisfied occupants per building: 50%, 60%, 70%, 80% and 90%. On the right side, the results are presented as a continuous line graph. Looking at these graphs, we observe that the percentage of buildings meeting 60% satisfied occupants is 11% if one considers votes from +1 to +3 as representing satisfaction, 47% if one includes votes from 0 to +3, and 83% if one includes votes from -1 to +3. If we look at 80% satisfied occupants per building, the number buildings meeting satisfaction dramatically decreases to 2% for +1 to +3 votes, 8% for 0 to +3 votes, and 22% for -1 to +3 votes. If we look at 90% satisfied occupants per building, the number buildings meeting satisfaction further decreases to 0% for +1 to +3 votes, 1% for 0 to +3 votes, and 12% for -1 to +3 votes.

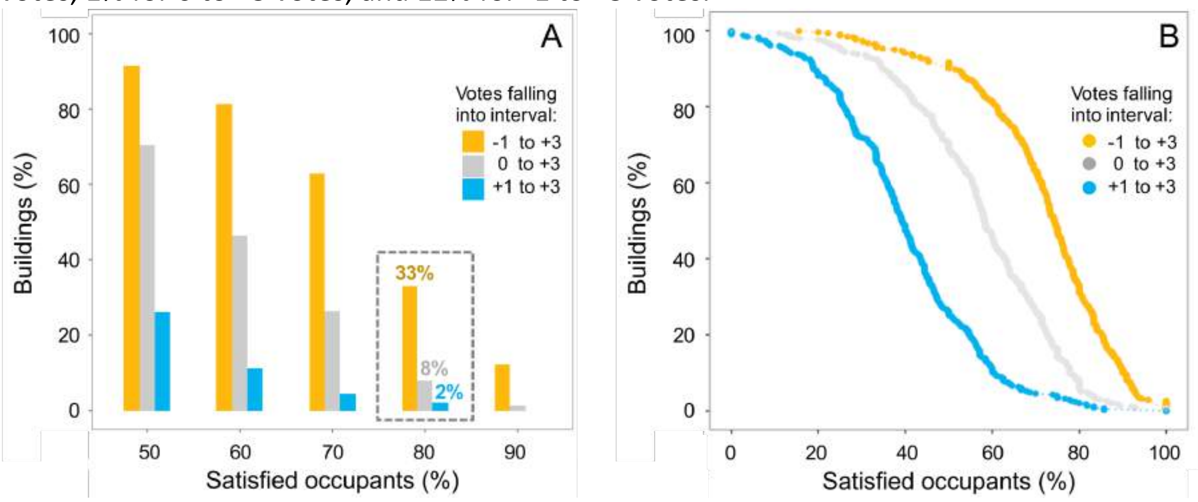


Figure 3: Bar chart (left) and line graph (right) showing the percentage of buildings meeting given percentages of occupants satisfied with temperature. The analysis is conducted for 3 satisfaction criteria ("-1 to +3", "0 to +3", "+1 to +3") based on surveys from 351 office buildings (52,980 occupants).

While occupant satisfaction used in framework of the long-term evaluations are not bound to a performance objective, ASHRAE Standard 55 details the metrics of thermal acceptability (for short term assessment) and PPD (for design purposes) having both a performance objective set at 80% occupants reaching comfort. This shift in metrics and assessment methods can lead to misunderstanding in the interpretation of the standard. If we were to assume a similar threshold for temperature satisfaction, the number of complying buildings would remain extremely low even when including 'slightly dissatisfied' among positive responses. This analysis questions the interval range and the potential survey performance objective that may be considered in the future certification programs.

4. Discussion

Many building certifications programs have recently adopted occupant comfort surveys into their credit structure. While this development positively addresses the need to assess and improve indoor conditions, the results observed on this study warn us about the dominance of negative feedback in regard to thermal comfort. The wider adoption of surveys in buildings leads us to discuss: (1) the difference in temperature satisfaction between certified and non-certified buildings, (2) the role that non-conventional HVAC systems may play in improving occupant satisfaction rates, and (3) the appropriateness of definitions, metrics and methods currently used for the assessment of thermal comfort.

4.1. Green certified vs. non-certified buildings

The wider adoption of surveys into green certifications programs (e.g. WELL Building Standard (IWBI 2014), LEED BD+C v.4 (USGBC 2013), LEED O+M v.4 (USGBC 2017), Green Mark (BCA 2015)) brings the question of occupant satisfaction for green-certified. IEQ is commonly part of the credit structure and therefore one may expect differences between certified and non-certified buildings. A study from 2013 involving 65 LEED certified (10,129 occupants) and 79 non-LEED certified buildings (11,348 occupants) have shown no practical difference in temperature satisfaction ratings between the two types (Altomonte and Schiavon 2013). The dominance of negative feedback observed in this study is likely to apply to current green certified buildings considering the current methodologies.

4.2. Non-conventional HVAC systems

The analysis conducted in this paper mainly reflected US conventional all-air buildings. We may wonder if radiant systems or occupant-centric approaches to comfort (personal comfort systems (PCS) and occupant vote-based HVAC control) have potential to address this concern.

We compared thermal satisfaction in 26 radiant (1645 subjects) versus 34 all-air (2247) buildings (Karmann et al. 2017). We found that radiant and all-air spaces have equal indoor environmental quality, including acoustic satisfaction, with a tendency towards improved temperature satisfaction in radiant buildings. Therefore, radiant systems may not be a strong enough solution. It is worthy to notice that this dataset had better buildings than the one described in this paper, in fact, both radiant and all-air buildings showed higher satisfaction (e.g. 54-59% of the buildings meeting the criteria for the -1 to +3 range, instead of 33% here).

PCS consist of heating and cooling devices (such as a heated/cooled chair, foot warmer, desk fan) used by individuals to control their local thermal environment and meet their comfort needs or desires (Zhang, Arens and Zhai 2015). Field studies involving PCS have shown considerably higher levels of temperature satisfaction than in conventional systems (Bauman et al. 2015, Zhang et al. 2015, Schiavon et al. 2016) suggesting positive effects of individual control and instant feedback over thermal comfort conditions. Yet, there is still limited survey data (especially over longer time periods and with a larger building count) confirming these promising results.

Occupant vote-based HVAC control (e.g. Comfy^{tm} (Comfy 2016)) allow occupants to directly interact with their building's air systems using their desktop or smartphone. The algorithm used in the background organizes occupant feedback and actuates thermal changes within the workspace. This ability for occupants to decide and the gratification resulting from instant reward (warm/cold input) is currently proving its success from a market perspective. Yet, there is a lack of third party field data able to confirm thermal comfort improvements.

4.3. Survey methodology

Long-term evaluations surveys were primarily developed as a diagnostic tool. Building managers interested in understanding how indoor environment affects occupants could request it. Dissatisfied temperature votes would generally be followed by branching questions intended to capture source of discomfort. Building managers could decide if survey results would be disclosed and whether actions (improvements to the building services) were taken. Using surveys as a compliance tool naturally brings up two issue. First, how many people should be satisfied to get the certification points, and second, what should be done if a building performs poorly. Transferring occupant survey methodology from diagnostic tool to compliance mechanism may be more delicate than it first appears, making it all the more relevant to clarify the metrics, scales and interval ranges used.

A key question relates to the use of 'satisfaction' as primary metric for long-term assessments. In short-term thermal evaluation, we can use thermal preference (wanting warmer, cooler or no change) or occupant behaviour to assess occupant desire, and the standard suggests using thermal sensation and acceptability. Thermal preference does not work well in 'long-term' assessment where we are trying to get an overall assessment of the thermal environment. Yet, by definition, 'satisfaction' depends on the fulfilment of 'wishes, expectations, or needs' one person may have (Oxford Dictionaries 2017). Therefore, we may wonder if thermal conditions are judged fairly across buildings or whether they depend on occupant's expectations for a given building or type of building leading to a certain bias in the assessment. This leads us to question the appropriateness of the metric used and its desirable level of tolerance.

The ASHRAE 55 standard has the objective to "specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space." It also defines a thermal acceptable environment as "a thermal environment that a substantial majority (more than 80%) of the occupants find thermally acceptable." We could argue that the long term assessment of the environment could be carried out using a 'long term' thermal acceptability question. This would reduce the issue related to satisfaction but would imply a change in many post occupancy evaluation tools that used satisfaction for decades.

5. Conclusions

We used a subset of the CBE Occupant IEQ survey database (52,980 occupants in 351 office buildings) to determine how many buildings fulfil comfort standards objectives. We found that 43% of the occupants are thermally dissatisfied, 19% neutral and 38% satisfied. The percentage of buildings providing a 'satisfactory' thermal comfort to at least 80% of their occupants is 2% if one considers votes from +1 to +3 ('slightly satisfied to very satisfied') as representing satisfaction, 8% if one includes votes from 0 to +3 ('neutral to very satisfied'), and 33% if one includes votes from -1 to +3 ('slightly dissatisfied to very satisfied' – the seemingly generous criterion suggested in ASHRAE Standard 55). If surveys are to be commonly and systematically used in building certification programs, it may be worth verifying the quality of the information captured, and the appropriateness of metrics, scales and interval ranges used.

6. Reference

Altomonte, S. and Schiavon, S. 2013. Occupant satisfaction in LEED and non-LEED certified buildings. *Building and Environment*, 68, pp.66–76.

ANSI/ASHRAE 2013. *Standard 55-2013, Thermal environmental conditions for human occupancy*. Atlanta, GA, USA: American National Standards Institute, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ANSI/ASHRAE 2017. *Standard 55-2017, Thermal environmental conditions for human occupancy*. Atlanta, GA, USA: American National Standards Institute, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Bauman, F., Zhang, H., Arens, E., Raftery, P., Karmann, C., Feng, J.D., Zhai, Y., Dickerhoff, D., Schiavon, S. and Zhou, X. 2015. Advanced Integrated Systems Technology Development: Personal Comfort Systems and Radiant Slab Systems.

BCA 2015. *Green Mark for New buildings (Non-residential)*. Singapore: Building and Construction Authority.

Comfy 2016. Comfyapp. *Comfy*. Available from: https://www.comfyapp.com/ [Accessed December 19, 2017].

De Dear, R.J., Brager, G.S., Reardon, J. and Nicol, F. 1998. Developing an adaptive model of thermal comfort and preference/discussion. *ASHRAE transactions*, 104, p.145.

Fanger, P.O. 1970. *Thermal comfort. Analysis and applications in environmental engineering.* Copenhagen, Denmark: Danish Technical Press.

Frontczak, M., Schiavon, S., Goins, J., Arens, E., Zhang, H. and Wargocki, P. 2012. Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. *Indoor air*, 22(2), pp.119–131.

IWBI 2014. *WELL Building Standard® v1.0*. New York, NY, USA: International WELL Building Institute, Delos Living LLC.

Karmann, C., Schiavon, S., Graham, L.T., Raftery, P. and Bauman, F. 2017. Comparing temperature and acoustic satisfaction in 60 radiant and all-air buildings. *Building and Environment*, 126, pp.431–441.

Nicol, J.F. and Humphreys, M.A. 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and buildings*, 34(6), pp.563–572.

Oxford Dictionaries 2017. Oxford Dictionaries | The World's Most Trusted Dictionary Provider. *Oxford Dictionaries*. Available from: https://www.oxforddictionaries.com/ [Accessed December 19, 2017].

Schiavon, S., Yang, B., Donner, Y., Chang, V.-C. and Nazaroff, W.W. 2016. Thermal comfort, perceived air quality, and cognitive performance when personally controlled air movement is used by tropically acclimatized persons. *Indoor Air*.

Shove, E. 2004. *Comfort, Cleanliness and Convenience: The Social Organization of Normality (New Technologies/New Cultures)*. Berg Publishers.

USGBC 2013. *LEED BD+C: New Construction v4 - Innovation*. U.S. Green Building Council. Available from: http:// www.usgbc.org/credits/new-construction/v4/innovation- catalog.

USGBC 2017. *LEED v4 for Operations and Maintenance*. U.S. Green Building Council. Available from: https://www.usgbc.org/resources/leed-v4-building-operations-and-maintenance-current-version.

Zagreus, L., Huizenga, C., Arens, E. and Lehrer, D. 2004. Listening to the occupants: a Web-based indoor environmental quality survey. *Indoor Air*, 14(s8), pp.65–74.

Zhang, H., Arens, E., Taub, M., Dickerhoff, D., Bauman, F., Fountain, M., Pasut, W., Fannon, D., Zhai, Y. and Pigman, M. 2015. Using footwarmers in offices for thermal comfort and energy savings. *Energy and Buildings*, 104, pp.233–243.

Zhang, H., Arens, E. and Zhai, Y. 2015. A review of the corrective power of personal comfort systems in non-neutral ambient environments. *Building and Environment*, 91, pp.15–41.

Windsor Conference
Rethinking comfort
12th - 15th April 2018

Revisiting overheating indoors

Runa T. Hellwig

E2D Energy Efficiency Design, Augsburg University of Applied Sciences, Augsburg, Germany
runa.hellwig@hs-augsburg.de

Abstract: In recent years, an increasing amount of overheating issues in buildings has been reported. Despite available knowledge and recognition of the problem by research, in practice little attention has been paid to the problem. The aim of the paper is to identify contradictions, missing interconnections, communication deficits or barriers. Terminologies used, and time and dynamics in the context of overheating and heatwaves will be discussed. Planning pathways and their consequences on preparedness for overheating or heatwaves will be discussed subsequently. In the context of overheating as well for heatwaves, informing people about the human ability to acclimatise to seasonal changes and addressing acceptable healthy temperature ranges instead of comfort ranges could be supportive in relaxing people's expectations towards indoor climate. Three areas should become a focus of future activities: a) enhancing adaptability in humans b) managing human expectation towards the indoor environment and c) enhancing adaptability of buildings. Time and dynamics in building performance, adaptation processes and mortality predictions are interrelated and will require more attention in future studies.

Keywords: heatwave, adaptability, adaptive, expectations, air-conditioning

1. Introduction

Climate change causes us to adapt our built environment and to rethink our accustomed routines towards our built environment. While in Europe optimising buildings for heating energy performance was the focus in the past, warm season free-running performance was not. What is being reported from practice is an increasing amount of overheating issues in buildings (e.g BRI Special issue 2017, Lomas & Porritt 2017). Although post-war buildings already tended to be overheated due to large transparent areas in the facades and a lack of thermal inertia (e.g. Grandjean 1969, Roaf et al. 2009), overheating has become a severe problem since the implementation of highly energy efficient strategies for winter.

As cooling technologies are available and have become affordable; and a warming world is the outlook, planners are concerned about litigation issues they could face (e.g. Hausladen et al. 2004; Roaf & Boerstra, 2015) and go for the 'safe' choice: active cooling (as a building's design might not be challenged by an engineer). In Germany for instance, compared to 15 years ago, considering active cooling has become almost a matter of course. Area-wide adoption seems only to be a matter of time.

A literature search identified areas of research in the context of overheating: heatwave mortality projections, health impacts, prevalence of elevated temperature indoors, heatwave warning systems, comfort models and standards/assessment methods, deterministic and stochastic studies on design impact, surveys on prevalent behaviours during warm periods, and human heat adaptation (for recent studies see e.g. BRI 2017). This is rather comprehensive knowledge and the question arises why besides the recognition of the problem of overheating by research, "…the matter is paid little attention in practice" (Lomas & Porritt (2017, p2).

The aim of the paper is to identify contradictions, missing interconnections, communication deficits or barriers towards successfully applying available knowledge on overheating avoidance in practice. The author would like to summarise important pieces of knowledge and research first, on which the discussion of selected points will be based on later. Finally, implications for future actions will be drawn.

2. Overview on selected research

2.1. Sustainability strategies

There is a trinity strategy for reaching sustainability: efficiency (less resource use per unit of service), consistency (ecologically sound technologies) and sufficiency (right measure). The first two have already been implemented in design, planning or operation procedures. Sufficiency is not yet a generally accepted strategy. Efficiency and consistency alone will not lead to sustainability because of rebound effects diminishing the effectiveness of the implemented measures. While efficiency and consistency are seen to be linked to technology application, sufficiency refers more to changes in consumption patterns. Although sufficiency has often been misunderstood as a lack of comfort or even backwardness it could also be seen as a simplification of life or liberation from overabundance; it is often associated with behavioural change, or as a modification of consumption patterns (Fischer et al. 2013).

Sustainability rating systems (e.g. LEED, BREEAM, BNB/DGNB, CASBEE, Green Star, Green Mark) are aimed at balancing the ecological, economical and socio-cultural aspects of our built environment. Sufficiency can be influenced through changes in the socio-cultural column (here: thermal comfort). A building’s passive design determines the overall potential for the magnitude of energy demand, and hence is also linked to sufficiency.

2.2. Overheating and Heatwaves

The term *overheating* has been used for temperatures exceeding defined acceptable temperatures (‘comfort’, see 2.4&2.3) in a warm or cold season. In the context of heatwaves *excessive heat* or *excess heat* are the terms used. The World Meteorological Organisation (WMO, 2015) recommends developing heatwave characteristics for individual regions considering the magnitude, the duration and their combined effect (severity) as well as the heatwave’s geographical extent. Heatwaves are often defined as two or three consecutive days with the daily outdoor mean temperature exceeding a threshold value (WMO, 2015).

According to the Intergovernmental Panel on Climate Change heatwaves will cause: a higher mortality, especially when occurring earlier in the warm season, and an increased temperature related morbidity (cardiovascular, respiratory, kidney diseases) (Smith et al. 2014). Hereby, “*Variability in temperatures is a risk factor in its own right, over and above the influence of average temperatures on heat-related deaths.*” (ibid., p713).

Earlier mortality projections are based on static temperature approaches leading to increased projected mortality in the future. Studies (e.g. Armstrong et al. 2011) found different health relevant threshold temperatures for different local climates. Therefore, Gosling et al. (2017) compared six different modelling adaptation methods for 14 European cities in order to compare their impact on the resulting mortality rates (period 2070-2099). Across all of the cities investigated and irrespective of climate/emission modelling, they found that the difference between including and excluding adaptation ranges was between 28% with one and 103% with another method. They concluded that adaptation should not be neglected in future mortality projections.

In future mortality/morbidity projections the quickening of the mean outdoor temperature change from one day to another, both increase >95% percentile and decrease <5% percentile, was considered (equalling +3.5 and -3.6 K resp. in current German climate; Zacharias & Koppe 2015). Diurnal temperature ranges in a heatwave, >95% percentile of the location's range, are also regarded as a stress factor (equalling 12.9 K in current German climate, ibid.).

The German Guideline on heatwave plan development on a regional level identified the following vulnerable groups of people requiring special consideration: elderly, socially isolated including the homeless, obese, people in need of care or with chronical diseases, dementia, special medication, sensitivity to heat, babies and small children (BMUB, 2017). Although sensitivity to heat or high temperatures has been reported to be decreasing (Boeckmann & Rohn, 2014), a higher impact is expected for non-acclimatised people compared to acclimatised (Maloney & Forbes 2011).

2.3. Adaptation to heat

When thermal stress disturbs homeostasis, the immediate response of the human body is thermoregulation (accommodation after Taylor 2014, see comprehensive review); repeated exposure to the stress leads to thermal adaptation, which can be classified into acclimation (artificially induced) or acclimatisation (seasonal or after changed residency). In active acclimation training or experiments two general approaches exist, the classical constant stress approach and the progressive overload or constant strain approach. The latter will lead to a higher degree of adaptation (ibid.). In heat, short-term adaptation goes along with a stabilisation of the cardiovascular system, decreased heart rate, increased sweat rate, lowering of the temperature threshold for sweating and vasodilatation, and lower resting core temperature (e.g. Wendt et al. 2007). After long-term adaptation a habituation of the body's responses (reduced sweat rate,) can be observed; they go along with a decrease in perceived strain as well as a modification in temperature perception (Taylor, 2014). Acclimatisation will not occur if a certain behaviour removes the stress. These could be air-conditioning, buildings sealed from the outdoor climate or rarely spending time outdoors and determine the extent to which acclimatisation will occur. Heat adaptation, once acquired by the body can be re-established in a shorter time than it took to establish adaptation at first (ibid.).

Office work of seasonal acclimatised subjects in an overheated realistic office environment during 4.3 h at temperatures 1 to 6 K above adaptive comfort Cat II (equalling 4 to 24 Kh exceedance per day, EN15251) goes along with gradually reduced willingness to exert (work) effort and less relaxed subjects (Hellwig et al. 2012).

2.4. Adaptive thermal comfort

The classic adaptive thermal comfort model is based on the human ability to adapt to thermal stimuli in three ways: behavioural adjustment, psychological adaptation and physiological adaptation (Nicol&Humphreys 1973, Auliciems 1981, de Dear&Brager 1998).

The current adaptive models of thermal comfort (ASHRAE St 55 2017, EN 15251 2007) determine the range of acceptable operative temperature (often referred to as comfort range) as a function of the prevailing outdoor temperature. The prevailing outdoor temperature has been defined as an exponentially-weighted running value with α being a constant found to best correlate with the indoor comfort temperature at a value of 0.8 (e.g. McCartney&Nicol 2001). ASHRAE St 55 (2017) recommends values of α between 0.9 and 0.6 with 0.9 more suitable for climates having a small day-to-day temperature dynamics and 0.6

for larger day-to-day temperature changes. It serves as a measure of the thermal experiences people collect from the recent outdoor weather and on which they develop parts of their actual expectations.

Alliesthesia is a concept[1] useful to describe phenomena in dynamic thermal environments or for locally varying stimuli on the body (intended or not) (e.g. latest paper Parkinson&de Dear 2017) and to understand the construct of perceived control (Hellwig, 2015).

2.5. Building design and planning

Overheating assessment is based on parameters of excess over upper acceptable temperatures (e.g. Nicol et.al 2009, Lomas&Porritt 2017), targeting time of exceedance, severity and/ or upper limit, e.g. CIBSE TM52 (2013 based on EN 15251 2007) applies three criteria of which at least two have to be complied with: 1: exceedance hours of Tmax (≤3%, occupied hours, non-heating season); 2: daily degree hours ≤ 6 Kh; 3: all temperatures in occupied hours < Tmax+4.

Wilson (2017) proposes a habitability test for buildings in the U.S.: a resilient design module to be implemented in the LEED assessment procedure aiming on maintaining thermal habitability of buildings, hence 'liveable temperatures' over a period of seven days during a power outage allowing for 5 or 10 Kd SET above 30°C SET for residential/ non-residential buildings.

Passive design theory of buildings, design recommendations for warm seasons, or simulation tools were established many years ago (e.g. Koenigsberger et al, 1973, Krause 1974, Hauser 1978). The positive impact of both, limited window-to-wall-ratios and effective solar shading, is nothing new but led to tightened mandatory requirements in Germany (DIN 4108-2 2013) which can be bypassed if compliance based on dynamic thermal simulation is shown. While today's buildings tend to be light-weight buildings the impact of thermal inertia is well-known and has been confirmed in simulation studies (e.g. Schlitzberger et al. 2017) and on the basis of occupant survey data (Gauthier et al. 2017). In this regard, both approaches also demonstrated the importance of heat dissipation by means of night ventilation as also implemented in assessment standards (DIN 4108-2 2013). The difficulty in implementing these strategies into designs has been repeatedly expressed by planners as well as reservations to use future TRY for simulation (e.g. Fischer 2013).

3. Discussion

Although the knowledge on overheating is already rather comprehensive the knowledge transfer has not been overly successful as planning practice shows. First some points regarding terminologies will be discussed. Then, time and dynamics will be discussed as they are important in both, overheating and heatwaves. The planning pathways and their consequences on preparedness for overheating/ heatwaves will be discussed subsequently.

3.1. Terminology

Terminologies often carry certain connotations which reflect attitudes or conventions of everyday life. Connotations or laypersons' understanding of selected terminology in the

[1] How a subject perceives a certain stimulus depends on whether the stimulus contributes to improve the internal state of the subject (positive, pleasant) or impairs the internal state of the subject (negative, unpleasant) (Cabanac 1971). Pleasure serves to reward behaviour and to provide motivation to exercise behaviour beneficial for physiological processes (Cabanac 1996).

context of overheating or heatwaves and the consequences arising from this are discussed as follows.

Comfort

When communicating issues of indoor temperature (here: overheating) normally the term *'comfort'* has been used. At least in the German language meaning, *comfort - Behaglichkeit*, has a strong connotation of cosiness and well-being; and this meaning is shared with English. In most German publications, in every day planning, in sustainability rating systems *Behaglichkeit* has been replaced by *Komfort* (nothing else than the English *comfort* was meant) but has a strong connotation of convenience for most lay persons. Furthermore, *comfort* is something that is seen as being *provided.* Can building professionals be seen as providers of comfort and can occupants be seen as passive recipients of comfort (de Dear et al. 1997, p3)? Could it be that the pronunciation on *comfort provision* as a service of building professionals not only "…may deny occupants simple facilities for discomfort alleviation…" (Bordass&Leaman 1997, p192) in the design process but may add to an occupant's impression that the locus of indoor climate control is was an external one?[2] And doesn't it support the widespread opinion among professionals that occupants exert 'unsuitable' behaviour? On this basis, isn't it logical that occupants would demand changes from the *comfort provider* (e.g. complaint rate)? If this was the case, would there be ways to shift this learnt attitude back towards occupants taking on responsibility for their comfort and actively *seeking* comfort? Further, would building professionals accept not being providers and would it change their ways of designing buildings?

The origin of *providing comfort* probably comes from the promotion of new technological achievements which are about to be brought onto the market, carrying a marketing promise which is *providing comfort.* Such a pattern can be observed repeatedly in practice, e.g. *smart buildings.* Although this marketing promise results in high user expectations which later may not be (fully) satisfied, it may help to further establish *comfort provision* rather than rejecting it.

Stress and adaptation

Even though there is broad evidence from field studies for acceptability or satisfaction in free-running buildings (here: in a warm season), stakeholders in the building process frequently express reservations about the adaptive comfort approach because of the necessary *adaptation* which they assume to cause *stress* (own experience from discussions with professionals, see also de Dear et al. 1997, p30). *Stress* in colloquial language carries an unhealthy connotation. Seasonal acclimatisation to heat is a slow process which physiologists regard as a "…fine-grained adaptation strategy,… [producing]...generalists." (Taylor 2014, Tab1). Although a slowly increasing temperature is seen as mild strain by physiologists, in colloquial language this would probably mean that the 'strain' is not recognisable.

[2] The concept of locus of control has been used to describe generalised expectancies towards the belief of being in a position (internal locus) or not (external locus) to cause a change (Rotter 1966). This concept was applied as one impact factor on the individual's level in a conceptual approach of perceived control by Hellwig (2015).

Healthy temperature

Whereas *comfort* and *adaptation* in an overheating context have been discussed controversially, e.g. the extension of the tolerable temperature range in a warm period from an occupational health and safety perspective (at outside temperatures above 26°C) saw a smooth implementation in Germany, even though the indoor temperature was allowed to increase from 26°C, 30°C up to 35°C provided certain supportive measures (adaptive opportunities) are applied (Hellwig&Bux 2013). Discussions in the working group comprising stakeholders from various fields including representatives of unions and employers (as experienced by the author personally) as well as the implementation into practice (as reported from the Federal Institute for Occupational Health and Safety) took place in an objective and factual way, very different from discussions on whether it would be OK to have just a few hours of slight exceedance in an office in a warm period.

From the brief discussion above it may be concluded that comfort could be seen as a highly emotionally loaded term, adaptation may be too much associated with stress whereas healthy temperature appears as a rather neutral to positive term.

3.2. Time and dynamics

Time and dynamics are important factors in overheating and heatwaves, in human adaptation and building performance.

Heatwave mortality projections

Gosling et al. (2017) found that with a static temperature assessment approach mortality rate was overestimated by 30 to 100% compared to approaches considering an adaptation effect. Their study gives cause to seriously considering the modelling of human adaptation in mortality predictions as it is "…a source of uncertainty that can be greater than the uncertainty in … climate modelling…". However, the concept of the running or prevailing mean outdoor temperature (EN 15251 2007, ASHRAE St 55 2017) is currently only applied to comfort questions. It would be interesting to see whether this concept could also serve as a suitable approach to mortality predictions allowing its use to consider dynamics in mortality prediction as well.

Heatwave severity, on- and offset

In dependence on the variability of the prevailing climate in a certain location, there can be different resulting sensitivities in the perception of the severity or on- and offset of heatwaves. Therefore, Nairn & Fawcett (2015) developed the excess heat factor (EHF) which is the product of two indices, one indicating the presence of an unusually warm period (3-day-mean minus annual 95% outdoor temperature percentile) and the second representing the level of acclimatisation at a certain time of a year (3-day-mean minus running monthly mean outdoor temperature). Again, the already developed concept of an outdoor running mean (with α varying according to location) as described earlier in this paper could also serve as one indicator as part of such an index.

What is the gradient in increase or decrease of temperatures, outdoors and indoors that would be still tolerable in the context of health protection? Zacharias and Koppe (2015) used the 5% (-3.6 K) and 95% (+3.5K) percentile of day-to-day mean differences (German weather) and the latter approach was also applied to diurnal temperature ranges (12.9 K). In the 2003 heatwave in Munich a decrease of the mean daily temperature of 6 K and 5 days with diurnal temperature ranges of 13 to 15 K were recorded (own data). No systematic data are available on the prevalence of diurnal temperature ranges or day-to-day mean differences indoors (although many monitoring projects have collected temperatures continuously and innumerable dynamic simulations have been carried out). Own data from the 2003 heatwave show a 4 K diurnal variability always above the adaptive Cat II upper temperature value in a light-to-medium-weight E-W-oriented setting with insufficient shading, a fairly high window-to-wall-ratio and no night ventilation but not air-tight as well as non-insulated.

Buildings

As there is a time lag in adaptation and harsh changes can be indeed stressful to cope with buildings should serve as a buffer. Early acclimatisation responses of the body take 3 to 6 days; the later responses require 7-14 days to develop (Wendt. et al. 2007). In dependence on the magnitude of outdoor temperature increase, solar loads and building design and airing, the full development of the maximum indoor temperature can take up to 10 days (Krause, 1974). For a building, in order to be supportive in the acclimatisation process there should be a delay of about one week, this being beneficial for avoiding standard warm period overheating as well. The before-mentioned light-weight building in the 2003 heatwave in Munich showed *no lag* - the indoor-outdoor temperature difference was almost the same over consecutive days during the rising temperatures of the heatwave.

The classification of buildings according to their effective thermal mass (DIN EN ISO 13790), calculation methods for a building's time constant as well as for heat source-to-sink relation are available. But these are abstract values which cannot be easily related to diurnal temperature ranges or time lags in maximum temperature development. So far, dynamic thermal simulation is carried out in order to determine excess temperatures or to show compliance with acceptable temperature ranges. Characteristic dynamic values as mentioned above are not yet part of typical analyses of results nor do benchmark values or recommendations exist.

The predictability and reliability of a building's thermal behaviour is an important building property for occupants (Bordass&Leaman 1997). A building that reacts 'even-tempered' and 'calm' to changes in outdoor weather would lead to a higher conformity of a user's expectation and actual building performance, hence a higher user satisfaction. This building property is highly linked to a time lag in the outdoor temperature to be mirrored attenuated indoors.

Field surveys

Field survey results reflect prevalent conventions, attitudes, expectations or behaviours at the survey's point of time. Field surveys have been used to develop adaptive comfort models. A changed attitude towards acceptable temperature ranges, overheating, or active cooling should then be reflected in such a result as well. On the one hand a changed attitude or expectation would be interesting to note. On the other hand, if we noted a changed *demand* towards lower temperatures in the warm season or a *demand* for active cooling where cooling was not common, would this give us reason to support this changed *demand* on the basis of the survey, developing an adjusted comfort model? Thus, would we end up with models reflecting the heat balance approach[3]? Nicol and Wilson (2013) asked: "Can it be written with natural ventilation as 'normal'?" Isn't there a need to find out what temperature range would be *sufficient* and *healthy* and then communicate this (certainly not neglecting special needs for groups of people)?

[3] ..as suggested by Fanger's expectancy factor.

The influence of time or dynamics appears to have been somewhat underrepresented in the discussion of overheating and heatwaves. It seems to be apparent that the time factors or dynamics in the different areas discussed are somehow interlinked and have a direct impact on the planning of buildings. If in heatwave predictions, heatwave severity assessment and building planning practice a similar or even the same variable would be used, this could enhance the understanding of the interrelation of outdoor weather impact on indoor temperature courses in addition to a better interdisciplinary exchange and transfer of new research results into practice.

3.3. Planning pathways and preparedness

Excellent human adaptability to temperatures can not only induce seasonal adaptation. If humans rarely spent time outdoors they would adapt to prevailing indoor temperatures. In the case of adaptation to actively cooled environments the temperature difference to cope with e.g. in a heatwave would be much higher compared to acclimatised persons. Although there is a lack of data from the field, the impact of cooling penetration on mortality/morbidity in heatwaves can be supposed.

Just as other countries and regions in Europe, Germany used to operate their buildings in a free-running mode in the warm season, in all residential, almost all school and the majority of office buildings. Classic air-conditioning systems were not well-accepted.

In 2007 EN 15251 introduced two comfort models in one standard: the heat balance and as a new approach the adaptive model. Since then two models have been existing in parallel. In 2008, a sustainability rating system BNB/DGNB for office buildings was launched in Germany comprising the two comfort models, hence two planning pathways. Hereby, the same magnitude of credits is given to categories I, II or III of comfort independent of which comfort model was used. The separation into two models allows for one planning pathway that may lead to building designs not suitable to meet future resilience requirements. Furthermore, a heat balance pathway tolerates designs with additional energy use and is likely to be a barrier for optimising the passive building design *before* adding active measures. Regarding the two planning pathways, de Dear et al. (1997, p26) believe that the differentiation between the two comfort models is not “irreconcilable”.

The next point refers more to the technology side and arguments explaining intensified cooling penetration. A finding by Cabanac emphasised by Nicol&Humphreys (1973) is that humans tend to favour behavioural thermoregulation more than other forms of thermoregulation. Humans receive an immediate rewarding confirmation of their behaviour in causing a useful thermal stimulus contributing to improve the internal state (alliesthesia as interpreted by Hellwig, 2015). Decentralised air-conditioning units controlled by the occupants can provide such an immediate positive feedback as this technology provides an immediate perceptible cold stream of air, explaining at least partly why this technology is so successful. Since the late nineties a new technology, thermo-activated slab cooling/heating systems has been adopted quite fast. If operated in the originally intended way heat sinks in the environment are used (ground or indirect evaporation) and energy is only used for pumping the water. Operated in such a way the cooling capacity is rather limited and can help to replace intense night ventilation or the missing thermal mass in an otherwise light-weight building. More recently and frequently the system has also started to be used in combination with heat pumps for heating *and cooling*, the latter followed by an increase in cooling capacity. Despite the usefulness of the original approach, it seems that this technology is serving as a low threshold cooling service opening doors to implementing cooling in residential buildings and schools. There is unfortunately doubt that this trend will be reversed: Because of the coincidence of cooling demand and highest electricity generation from PV in the day, the use of daytime cooling with heat pumps is now also promoted by industry and consultants as an appropriate measure, hereby increasing the proportion of self-consumed renewable energy from PV systems, appearing to be even more sustainable. Also the fast penetration of activated concrete slabs for cooling (often pronounced cooling capacity from the ceiling) could be explained by alliesthesia, (here: spatial, as defined by Parkinson&de Dear 2015). If this technology is then to be thought of *energy-efficient* active cooling, then it would be the first measure of choice.

It is maybe for the above-mentioned two reasons, that seen against the scenario of increasing future temperatures, engineers, building operators and companies find that cooling has become what Walker, Shove & Brown (2014) call a 'need', even in regions where cooling has not been established widely so far. Shove (2017) argues that the approach of the equivalence of service as the basis for comparison of energy efficiency is one driver stabilising "…contemporary, but often recently established ideas, for instance about the meaning of comfort…". The principle of equivalence of indoor environment service is what the European Energy Performance of Buildings Directive sets as precondition for energy efficiency comparison of different solutions "…reinforcing the idea that such interpretations [here: thermal comfort requirements] are non-negotiable…" (ibid.). If comfort was a 'non-negotiable need', a planner could perceive a high pressure if he could not satisfy this 'basic need', followed by other issues, i.e. litigation issues. Before the background of these two arguments (attractiveness and need) a further spread of cooling appears to be almost unavoidable leading probably to more non-acclimatised people.

Earlier in this paper it was argued that occupants may not feel responsible to seek comfort and to exert behaviour because *comfort* would be *provided*. If this was the case it might be extremely difficult to initiate changes in behaviour. People with a (learnt) attitude of external locus of control (here: regarding comfort) tend to not benefit from information on e.g. appropriate behaviour in an overheated building or from explanations on how the building works because they don't believe they have the power to cause a change and they would probably tend to resist acquiring changes.[4]

Besides the already mentioned vulnerable groups, school children are often regarded as vulnerable because of their dependency on a person in charge, i.e. the teacher (BMUB 2017). Special guidance of teachers on how to support the children in warm periods could be a good solution, organising a changed schedule of lessons, encouraging the children to drink more, shifting more exhausting activities to cooler periods etc.. Non-exposure to warmth could mean to remove any stimulus to acclimatise to warm weather which would diminish the vulnerables' adaptability in the long term. Buildings should also therefore offer reasonable time lags in indoor temperatures rise compared to the outdoor temperature as already discussed above. van Marken Lichtenbelt et al. ("healthy excursions" 2017) propose using (temperature) fitness programs to enhance individual health in general or maybe even adaptability to heatwaves. Such programs could be customised for vulnerable groups as well. They might also be suitable carriers of the message that seasonal acclimatisation

[4] According to Bandura (1977) negative (social) verbal persuasion by others, e.g. by facility manager or planner saying: ‚Occupants always open the windows which has a negative impact on the energy consumption; it would be better if they didn't have access to windows!' This could cause occupants to think that they really would not have the *capability* to open the window at the right time. However this principle could also be used in a positive way.

occurs as the year progresses and that seasonal acclimatisation is supportive in coping with heatwaves.

There seems to be a mismatch between planning practice/attitude towards overheating avoidance on the one hand and the clear intention by health authorities that active cooling should be the last choice (for the non-vulnerable population). A broad consensus in society that active cooling measures will increase the vulnerability of humans in the long term seems to be necessary. How building occupants can be involved more intensively compared to current practice and how a shift of the current attitudes of all stakeholders in the planning process (Shove, 2003) could be achieved offers room for future research approaches. Shove (2017, p8) concludes that a solution would be to design buildings "…that do not meet present needs, and that do not deliver equivalent level of service, but that do enable and sustain much lower-carbon ways of life." For the planning practice, and in addition to the before mentioned more detailed consideration of building dynamics, it seems to be a necessary future step to develop an integrated model for acceptable temperatures. A first useful step would be of course if all buildings had to comply with minimum passive design requirements as suggested by Wilson (2017). Health-related fitness programs could help to increase the adaptability in the population.

4. Conclusion

In future discussions about temperatures in warm periods, both normal and during heatwaves, it might be useful to address targeted temperature ranges consequently as *acceptable temperature ranges* instead of *comfort ranges.* Addressing *healthy indoor temperature ranges* when it comes to exceptionally warm periods or even heatwaves seems to be appropriate for communicating the topic in a factual way. In order to address both, overheating in today's buildings and the projected higher frequencies of heatwaves two areas should become a focus of future activities: a) enhancing adaptability in humans, and b) managing human expectation towards the indoor environment (all stakeholders in the building process). A third area has already been in the focus of research: c) enhancing the adaptability of buildings, with some questions still remaining to be answered. The following points result from the discussion chapter:

Enhancing adaptability in humans

- relaxing expectations towards indoor climates
- information on the ability of humans to acclimatise to seasonal climate changes and that a good seasonal acclimatisation also helps in heatwaves
- developing suitable health programmes promoting e.g. staying outdoors
- developing fitness programs or special programs for vulnerable groups

Managing expectations

- relaxing all stakeholder's expectations towards indoor climates
- informing about the natural ability of humans to acclimatise to seasonal climate changes and that a good seasonal acclimatisation also helps in heatwaves
- providing information on healthy and sufficient temperatures and behaviour (continue to provide guidance on appropriate overheating mitigation and behavioural mitigation measures as part of heat-wave plans)
- managing occupants expectations on what free-running buildings can offer (sustainable occupancy) and what is *not* in the range of expectation (active cooling, constant temperature)

- informing about low energy use adaptive opportunities in free-running buildings, e.g. campaigns on how to best operate fans

Enhancing building adaptability

- informing stakeholders in the building process that good passive design can offer acceptable and healthy temperature for acclimatised occupants and that an acclimatised population can cope with heatwaves
- establishing adaptability planning (passive design compliance during heatwave scenarios)
- identifying ways to make passive design more appealing to stakeholders taking design decisions
- designing for acceptability which includes predictable thermal building behaviour and personal control
- designing for two design goals: cold *and* warm periods (variable solutions)
- developing and establishing interlinked information on required time lags in indoor temperature rise during warm periods and heatwaves in a certain region

The above list does not aim to be comprehensive and requires further discussion. From the list the great importance expectation plays for indoor climate perception can be noticed immediately. Developing an integrated model for acceptable temperatures (instead of formerly two comfort models) would be more than supportive in communicating indoor temperatures in planning practice. Transdisciplinary approaches and inter-disciplinary collaboration could help managing the change towards sustainable building design and operation.

5. References

Armstrong, B.G.; Chalabi, Z.;Fenn, B.;Hajat, S.; Kovats, S.; Milojevic, A.; Wilkinson, P. (2011): Association of mortality with high temperatures in a temperate climate: England and Wales. J Epidemiol Community Health, 65, 340-345.

ASHRAE/ANSI Standard 55:2017: Thermal environmental conditions for human occupancy. American Society of heating. Atlanta, Georgia, Refrigerating and Air-Conditioning Engineers.

Auliciems, A. (1981): Towards a psycho-physiological model of thermal perception. Int. J. Biometeor. 25, 2, 109-122.

Bandura, A. (1977): Self-efficacy: Toward a unifying theory of behavioral change. Psychological Review, 84, 2, 191-215.

Bordass, W.; Leaman, A. (1997): Future buildings and their services. Strategic considerations for designers and clients. Buildings Research and Information, 25, 4, 190-195.

Boeckmann, M.; Rohn, I. (2014): Is planned adaptation to heat reducing heat-related mortality and illness? A systematic review. BMC Public Health, 14, 1112.

BMUB Bundesministrium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (2017): Handlungsempfehlungen für die Erstellung von Hitzeaktionsplänen zum Schutz der menschlichen Gesundheit. Version 1.0, 24.March 2017

BRI Building research and Information (2017): Special issue on overheating. Building Research and Information, 45, 1+2

CIBSE Chartered Institution of Building Service Engineers (2013): Technical Memorandum TM 52: The limits of thermal comfort: avoiding overheating in European buildings. July 2013

Cabanac, M. (1971): Physiological Role of Pleasure. Science, 173, 4002, 1103-1107.

Cabanac, M. (1996): Pleasure and joy, and their role in human life. Institute of Public Health, Tokyo, Proceedings Indoor Air, 1996, 3, 3-13

de Dear, R.; Brager, G., Cooper, D. (1997): Developing an adaptive model of thermal comfort and preference. Final report. ASHRAE Report 884

EN ISO 13790:2008-09: Energy performance of buildings - Calculation of energy use for space heating and cooling (ISO 13790:2008); German version EN ISO 13790:2008

EN 15251:2007-08: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. German version.
Fischer Ch. (2013): Reader's letter and comment. Bauphysik, 35, 5, 361.
Fischer, C.; Grießhammer, R. (2013): When less is more. Sufficiency: Terminology, rationale and potentials. Oeko-Institute's Working paper 2/2013. Oeko-Institue e.V., Freiburg, Darmstadt, Berlin, October, 2013, www.oeko.de/oekodoc/1879/2013-007-en.pdf, last accessed 29.12.2017
Gauthier, S.; Teil, D.; James, P.; Stamp, S. (2017): Are heavyweight buildings more comfortable? The potential of thermal mass in increasing thermal comfort. Proceedings, Passive Low Energy Architecture PLEA Conference, Edinburgh, 2-5 July 2017, ISBN 978-0-9928957-5-4.
Gosling, S.; Hondula, D.M.; Bunker, A.; Ibarreta, D.; Liu, J.; Zhang, X.; Sauerborn, R. (2017): Adaptation to climate change: A comparative analysis of modelling methods for heat-related mortality. Environ Health Perspect, 125, 8, DOI: 10.1289/EHP634
Grandjean, E. (1969): Fenster und Raumklima: Untersuchungen über Sonnenschutzanordnung und raumklimatische Bedingungen in der warmen Jahreszeit. Schweizerische Bauzeitung, 87, 35, 649-656.
Hausladen G, Hellwig RT, Nowak W, Schramek ER, Grothmann T (2004) 26°C-Falsch verstandener Arbeitsschutz? (26°C – Misinterpreted occupational health and safety?) In German. Bauphysik 26, 4, 197-204.
Hauser, G. (1978): Method for calculating of thermal behaviour of buildings. Proceedings ICHMT-Seminar. Hemisphere Publishing Comp., Washington, 419-427
Hellwig R.T., Bux K. (2013) Workplace temperature requirements in the German Workplace Ordinance: revising the rule. Architectural Science Review 56, 1, 22-29. DOI: 10.1080/00038628.2012.746636
Hellwig, R.T.; Nöske, I.; Brasche, S.; Gebhardt Hj.; Levchuk, I.; Bischof, W. (2012): Heat strain and performance in offices at elevated outside temperatures. HESO Final Report. In German. Federal Institute for Occupational safety and Health, Dortmund, Berlin, Dresden, ISBN 978-3-88261-142-7. 65 pp
Hellwig, R.T. (2015): Perceived control in indoor environments: a conceptual approach. Building Research and Information, 43, No. 3, pp. 302-315. DOI: 10.1080/09613218.2015.1004150
Holmes, S.H.; Phillips, T.; Wilson, A. (2016): Overheating and passive habitability: indoor health and heat indices. Building research and Information, 44, 1, 1-19, DOI: 10.1080/09613218.2015.1033875
Koenigsberger, O.H.; Ingersoll, T.G.; Mayhew, A.; Szokolay, S.V. (1973): Manual of tropical housing and building. Part One: Climatic design. Longman, London, New York, ISBN 0582 44546 9
Krause, E. (1974): Die Stabilisierung des sommerlichen Raumklimas im Wohnungsbau und in thermisch vergleichbaren Räumen. Wissenschaftliche Zeitschrift der Technischen Universität Dresden, 23, 3-4, 833-836.
Lomas, K.J.; Porritt S.M. (2017): Overheating in buildings: lessons from research. Building Research & information, 45, 1-2, 1-18, http://dx.doi.org/10.1080/09613218.2017.1256136
McCartney, K.J.; Nicol, J.F. (2001): Developing an adaptive control algorithm for Europe. Energy and Buildings, 34, 623-635.
Maloney S.K., Forbes C.F. (2011): What effect will a few degrees of climate change have on human heat balance? Implications for human activity. Int. J. Biometeorology, 55, 2, 147-160.
Nairn, J.R.; Fawcett, R.J.B. (2015): The Excess Heat Factor: A Metric for Heatwave Intensity and its use in classifying heatwave severity. Int. J. Environ. Re. Public health, 12, 227-253, doi:10.3390/ijerph120100227
Nicol, J.F. and Humphreys, M.A. (1973): Thermal comfort as part of a self-regulating system. Building Research and Practice, 3, 174-179
Nicol, J.F.; Hacker, J.; Spires, B.; Davies, H. (2009): Suggestion for new approach to overheating diagnostics. Building Research and Information, 27, 4, 348-357.
Nicol J.F.; Wilson, M. (2013): A critique of European Standards EN 15251: strengths, weaknesses and lessons for future standards. Building Research and Information. 39, 2, 183-193. DOI: 10.1080/09613218.2001.556824
Parkinson, T.; de Dear, R. (2017): Thermal pleasure in built environments: spatial alliesthesia from air movement, Building Research and Information, 45, 3, 320-335, DOI: 10.1080/09613218.2016.1140932
Parkinson, T.; de Dear, R. (2015): Thermal pleasure in built environments: physiology of alliesthesia. Building Research and Information, 43, 3, 288-301, DOI: 10.1080/09613218.2015.989662
Roaf, S.; Crichton, D.; Nicol, F. (2009): Adapting buildings and cities for climate change. A 21st century survival guide. 2nd ed, Elsevier, Architectural press ISBN: 978-1-85617-720-7
Roaf, S.; Boerstra, A.C. (2015): Workshop WS 9: IEQ related litigation increase. Healthy Buildings Conference Europe, Eindhoven, The Netherlands, 2015, 18.-20.Mai 2015

Rotter, J.B. (1966): Generalized expectancies for internal versus external control of reinforcement. Psychological Monographs, 80, 1, 1-28

Shove, E. (2003): Users, technologies and expectations of comfort, cleanliness and convenience. Innovation, 16, 2, 193-202. DOI: 10.1080/13511610320001 12751

Shove, E. (2017): What is wrong with energy efficiency? Building Research and Information. DOI: 10.1080/09613218.2017.1361746

Smith, K.R.; Woodward, A.; Campbell-Lendrum, D.; Chadee, D.D.; Honda, Y.; Liu, Q.; et al. (2014): Human health: impacts, adaptation, and co-benefits. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field, C.B.; Barros, V.R.; Dokken, D.J.; Mach, K.J.; Mastrandrea, M.D.; Bilir, T.E.; et al. (eds.) Cambridge, UK and NewYork, NY: Cambridge University Press, 709–754.

Schlitzberger, S.; Kempkes, C.; Maas, A.; Schäfers, M. (2017): Einfluss der Wärmespeicherfähigkeit auf den Heizwärmebedarf und thermischen Komfort (Impact of the heat storage capacity on heating demand and thermal comfort). In German, English abstract and captions. Bauphysik, 39, 1, 57-63. DOI: 10.1002/bapi.201710008

Taylor, N.A.S. (2017): Human heat adaptation. Comprehensive Physiology. 4, 325-365. DOI: 10.1002/cphy.c130022

van Marken Lichtenbelt, W.; Hanssen, M.; Pallubinsky, H.; Kingma, B.; Schellen, L. (2017): Healthy excursions outside the thermal comfort zone, Building Research & Information, 45, 7, 819-827, DOI: 10.1080/09613217.2017.1307647.

Walker, G.; Shove, E.; Brown, S. (2014): How does air conditioning become 'needed'? A case study of routes, rationales and dynamics. Energy Research & Social Science, 4, 1-9. DOI: 10.1016/j.erss.2014.08.002

Wendt, D.; van Loon, L.J.C.; van Marken Lichtenbelt, W.D. (2007): Thermoregulation during exercise in the heat. Sports Med, 37, 8, 669-682

Wilson, A. (2017): Rethinking regulation post Hurricane Sandy. Presentation Slides, Passive Low Energy Architecture PLEA Conference, Edinburgh, 2-5 July 2017, ISBN 978-0-9928957-5-4. See Holmes et al. 2016

WMO World Meteorological Organization (2015): Guidelines on the definition and monitoring of extreme weather and climate events. Draft version – First review by TT DEWCE, December 2015. https://www.wmo.int/pages/prog/wcp/ccl/opace/opace2/documents/DraftversionoftheGuidelinesontheDefinitionandMonitoringofExtremeWeatherandClimateEvents.pdf, last accessed 14.1.2018

Zacharias, S.; Koppe, C. (2015): Einfluss des Klimawandels auf die Biotropie des Wetters und die Gesundheit bzw. die Leistungsfähigkeit der Bevölkerung in Deutschland. Umweltbundesamt (Hrsg.) Umwelt& Gesundheit 06/2015

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Changing Thermal Comfort Expectations: Studies in Darwin, Australia

Terence Williamson[1] and Lyrian Daniel[1]

[1] The University of Adelaide, School of Architecture & Built Environment, Adelaide, Australia, terence.williamson@adelaide.edu.au; lyrian.daniel@adelaide.edu.au.

Abstract: This paper presents an examination of the thermal expectations of occupants in naturally ventilated dwellings from two studies in Darwin, Australia, conducted some 25 years apart (1988/89 and 2013/14). The 25 years between the two studies have witnessed dramatic changes in Darwin, that include a doubling of the population, considerable differences in dwelling styles offered in the market, technological developments making the installation of air-conditioning more available, relative changes in incomes, and energy prices making air-conditioning more affordable. The 1988/89 study employed Comfort Vote Logger devices to record a total of 3800 comfort votes in 16 un-air-conditioned houses during the build-up and wet seasons. The 2013/14 study involved 20 mainly free-running houses in which thermal conditions were recorded on purpose built logging instruments while the occupants recorded 2535 comfort votes over a ten-month period. Analysis presented in the paper gives a detailed comparison of the results from the two studies covering four criteria central to the adaptive comfort concept - external versus indoor temperatures, thermal acceptability, thermal sensitivity and thermal neutrality. The paper concludes with a discussion of the findings and implications of these findings for the adaptive approach to thermal comfort.

Keywords: Thermal comfort; residential; longitudinal studies, tropical climate, natural ventilation

1. Introduction

Models of thermal comfort included within international Standards implicitly assume thermal expectations and therefore preferences are (time) invariant. However, it is generally agreed that, at least in part, thermal comfort is a social and cultural phenomenon which may change over time. For example, Chappells & Shove (2005) suggest that *"comfort is a provisional and always precarious social and cultural achievement"* (p 34) and go on to state that *"people's expectations of comfort have changed significantly over the last few decades"* (p 37). Similarly, Brager & de Dear (2003) suggest there exists a *"mutually dependent relationship between technological development and social and cultural expectation"* (p 177) citing the widespread availability of air-conditioning as *"dramatically influenc*[ing] *attitudes about comfort and building design"* (p 177). In Australia, the Nationwide House Energy Rating Scheme (NatHERS) fuels ever increasing expectations by stating that *"NatHERS helps to make Australian homes more comfortable for their inhabitants."* (NatHERS, 2017, http://nathers.gov.au/about). Following the logic of these statements, we would perhaps expect to be able to detect variations in thermal comfort expectations as social and cultural conditions change over time.

In their recent book, Humphreys and colleagues (2016) draw attention to the deficit in our understanding of thermal comfort over time, questioning whether "... *the relation between the climate and the desired indoor temperatures remained stable over the decades?"* (p 115) (i.e. with reference to the adaptive model of thermal comfort). Few, if any, research studies have specifically examined the question of changes in thermal comfort expectations of a population over an extended period of time. Understanding what changes might occur is particularly interesting in locations with tropical climates, such as Darwin in the north of Australia. Here early 'European-style' dwellings were adapted to the climatic conditions of the 'Top End' with expectations of thermal comfort grounded by what could be achieved by the best of these designs. While a small proportion of housing stock continues to be designed in a manner highly responsive to the local climate and lifestyle, the majority of new builds are informed by 'southern' building standards and styles, with comfort conditions largely achieved by mechanical cooling instead.

1.1. Expectations

The role of expectation in thermal comfort research was acknowledged in the early work of McIntyre (1980), who stated that "a person's reaction to a temperature which is less than perfect will depend very much on his expectations, personality, and what else he is doing at the time." Shortly afterwards, Auliciems, in his Hypothetical model of psycho-physiological warmth perception, developed the idea of expectations to account for "verbalized preferred sensations as opposed to neutral and comfortable" (Auliciems, 1981, p 116). Thermal expectations in his model have "climato-cultural determinants" (Auliciems, 1983).

Humphreys and colleagues (2016, p 91) have recently pointed out that different expectations may lead to different temperature preferences. In general, however, they associate these different expectations to 'physical factors' at the expense of considering that they may in fact be culturally or societally based. This is likely to be the case in Darwin where the nature of the thermal expectations generally encouraged in the Top End centres on a philosophy of living with the climate.

As an example, Phil Harris and Adrian Welke of Troppo Architects in Darwin published a short book, *Punkahs and Pith Helmets* in 1982 (Harris & Welke, 1982), that promoted the idea that good house design responded to the local climate and environment of the Top End, and, in particular, that residents should embrace a 'tropical living' life-style. In this book, they suggested that physical comfort is achieved when the inside can be constantly perceived to offer improved climate conditions compared to the outside without the aid of mechanical devices. This simple ideal defined the level of comfort expectation for housing and lifestyles when air-conditioning was less common. This ideal is still championed by many 'mavericks' on environmental grounds who rejoice in living in mostly free-running, naturally ventilated houses. The philosophy underpinning the thermal expectations of these Top End residents is clearly expressed in a response to a Northern Territory Government White Paper on Development of Northern Australia:

> *In the early to late 20th century, top enders adapted to this harsh climate with good house design (breezy, open, elevated), and a slower pace of life. People did not use or depend on air-conditioning …… It is my view that if you come to live in the top end, you should embrace and adapt to the environment you are living in. (Woodgate, 2014)*

This current paper seeks to understand whether the increase in exposure to air-conditioning or other societal changes can be seen to have altered these thermal expectations. The paper will present an examination of the thermal expectation of subjects in dwellings across two studies in Darwin, Australia, conducted some 25 years apart (1988/89 and 2013/14).

2. Details of studies

The following Sections provide background and details of the two studies dealt with in this paper.

2.1. Darwin

Darwin, the capital city of the Northern Territory, is a coastal town at latitude 12.24 South. Its monsoonal climate has two distinct seasons - the hot, wet season from November to March and the hot, dry season from May to September. October and April are transition months. Prior to the onset of the wet season proper, the 'Build-up' period (October to early December) is uncomfortably hot and humid. Only occasionally are there thunderstorms to provide some relief. October and November are the hottest months (average daily maximum temperature above 33°C) just prior to the increase in cloud cover associated with the 'Wet'. During these days the average diurnal temperature swing is ~7 °C and varies little from day to day. The wet season proper (December to March) is typified by periods of monsoon weather associated with heavy showers, often with afternoon or evening thunderstorms interspersed with sunny, hot and humid days. During the dry season, prevailing south-easterly trade winds result in mostly pleasant weather with warm to hot, sunny days, generally cloudless skies and relatively low humidity. The mean daily maximum temperatures are consistently high (average 30 °C to 32 °C) while the minimum temperatures average around 19 °C.

The 25 years between the two studies have witnessed dramatic changes in Darwin. In the 1980s Darwin was mainly a town of public servants with a population of around 72,000. By 2013, with growth of industries like mining and defence, the population had doubled. Over the years considerable differences in dwelling styles offered in the market have also been noted while technological developments have made the installation of air-conditioning more available. Relative changes in incomes and energy prices have also made air-conditioning more affordable with the penetration of air-conditioning increasing from 65% in 1988 to 96% in 2013 (ABS, 2014; Williamson et al., 1991). In 1985-86, average annual expenditure on energy was $765, the highest in Australia at the time due to the high cost of electricity generation in the Northern Territory (ABS, 1988). In 2012 this figure had increased to an annual bill of around $2080 (Australian Bureau of Statistics, 2012). Despite the substantial increases in household air-conditioning penetration and the cost of electricity, median household energy expenditure decreased from around 2.3% of annual household income in 1988 to 1.7% in 2015 (ABS, 2012). In 1988, approximately 20% of Northern Territory dwellings had swimming pools, often resulting in considerable energy consumption due to pump and filtration requirements, by 2007 this figure had increased to nearly 30% (Australian Bureau of Statistics, 2007).

The Darwin population is, compared with the rest of Australia, on average more highly qualified, has higher incomes, and a much higher proportion of the population is employed in the Government sector (Census, 2011). There is a larger proportion of rented, rather than owned houses, especially Government and Housing Authority properties, compared with the average in Australia (Census, 2011). As is the case throughout Australia, separate detached dwellings are the principal housing form (Census, 2011), although in recent years there has been a boom in high-rise apartment style housing.

2.2. 1988/89 Study

The general objective of the 1988/89 study was to obtain data about the thermal preferences for housing in the humid tropics with the aim of providing advice to designers on design times, and attitudes to and use of air-conditioners. The project was funded by the National Energy Research Development and Demonstration Council (NERDDC) and the University of Adelaide. The report of the study (Williamson et al., 1991) was finally published after the funding program was closed down.

In the course of the study a total of 3800 comfort votes in 17 un-air-conditioned houses and 3647 votes in 14 air-conditioned houses were recorded on Comfort Vote Logger devices during the build-up and wet seasons (October to March). Some examples of the houses included in the study are shown in Figure 1.

The Comfort Vote Logger (CVL) is shown in Figure 2. The original design for the device was carried out by staff and students in the Department of Electrical and Electronic Engineering, the University of Adelaide. The device was compact, easy to use and self-contained capable of recording a number of factors of interest in thermal comfort field studies. The user entered functions recorded by participants comprised:

1. Individual identification (up to four users)
2. Thermal discomfort (7-point scale)
3. Clothing level (three options)
4. Activity level (three options)
5. Plant operation/air movement (three options)

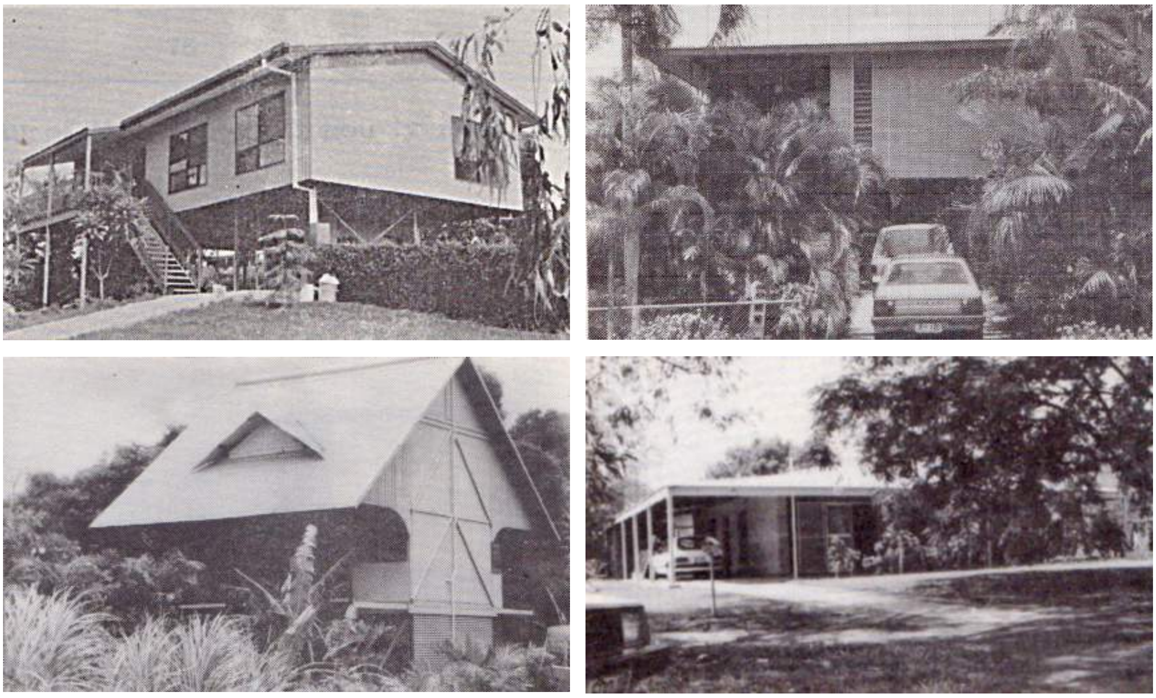


Figure 1. Examples of some of the houses in the 1988/89 study

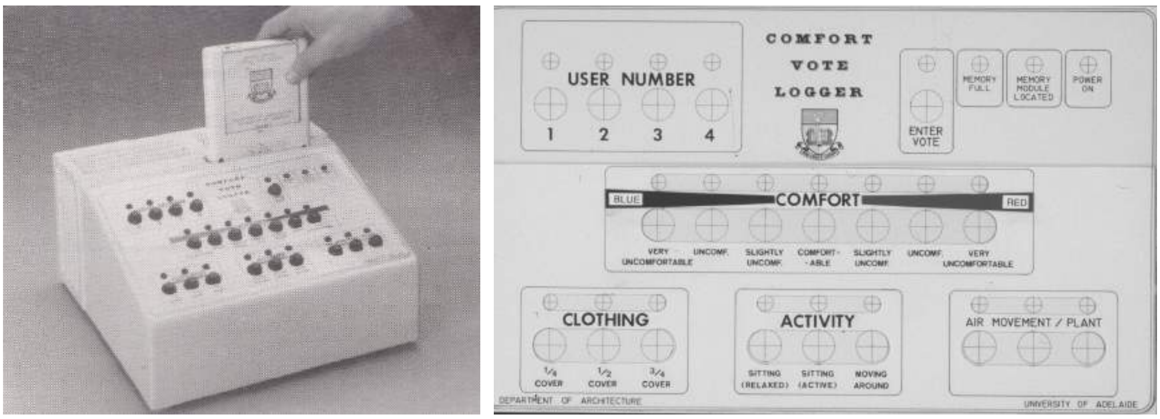


Figure 2. Comfort Vote Logger and detail of front panel

In addition to the user input information, the device provided for automatic recording of time, indoor air dry bulb temperature and relative humidity. The unit operated from a 240V power supply. The recorded data are stored in a removable 'Memory Module' containing two battery backed RAM chips capable of storing up to 2046 complete voting records. The comfort/discomfort scale displayed on the logger was based on the DISC scale of thermal discomfort developed by Gagge (1985). In personal communications, he recommended this scale rather than the ASHRAE Thermal Sensation Scale for studies in humid environments. DISC can be either positive or negative, negative values representing cold discomfort and positive values representing warm discomfort:

- Intolerable
- Very uncomfortable
- Uncomfortable
- Slightly uncomfortable
- Comfortable

On the logger a 7-point scale was shown with a cool/cold side (blue) and a warm/hot side (red) with the use described for the residents in a Comfort Vote Logger operating instruction manual.

2.3. 2013/14 Study

The 2013/14 study involved 20 households living in mainly free-running, naturally ventilated houses (Figure 4). It aimed to collect data on their thermal behaviour, expectations and preferences, in part, to inform national mandatory residential building performance assessment methods. Thermal conditions within the homes were recorded on purpose-built logging instruments (Figure 3) that enabled the collection of air-movement measurements that had previously been impractical to gather in large monitoring exercises (Daniel et al, 2014; 2015). In general, the data collection met the requirements of a Class II field study (ASHRAE, 2013).

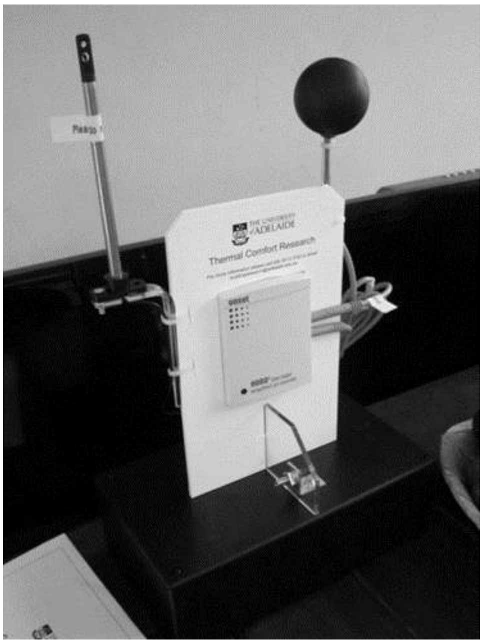


Figure 3. Monitoring device used in 2013/14 study

The occupants regularly completed paper-based thermal comfort vote surveys, returning 2353 over a ten-month period (note: one household did not return any thermal comfort vote surveys thus only 19 households are represented in the analysis below). The surveys were manually entered into Excel and matched to the corresponding environmental measurements. The thermal comfort vote surveys included the ASHRAE seven-point thermal sensation scale, McIntyre's three-point preference scale and a six-point comfort scale, as well as questions relating to activity level, clothing arranged and operation of heating or cooling devices.

Figure 4. Examples of some of the houses in the 2013/14 study

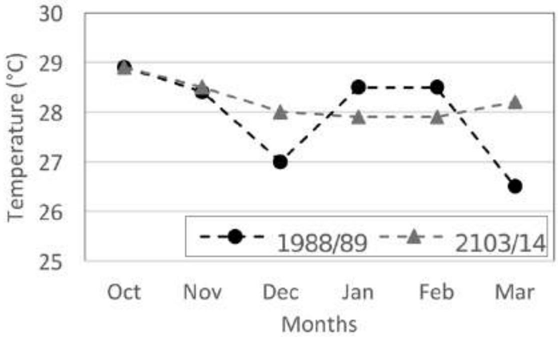
3. Preliminary comparisons

For an equivalent comparison between the two studies, analysis is limited here to the build-up and wet periods, that is, the months October to March. In addition, only votes from occupants 20 years of age or more are considered.

3.1. Temperature and humidity

Figure 5 shows the mean monthly outdoor temperature and relative humidity levels during the two study periods. These data have been derived from climate weather files of hourly data[1]. Over the whole study months, the average external temperature in 1988/89 was about 0.8K cooler compared to 2013/14. On the contrary overall relative humidity in 1988/89 was some 3% higher.

[1] Climate data files supplied by Exemplary Energy Partners, Canberra



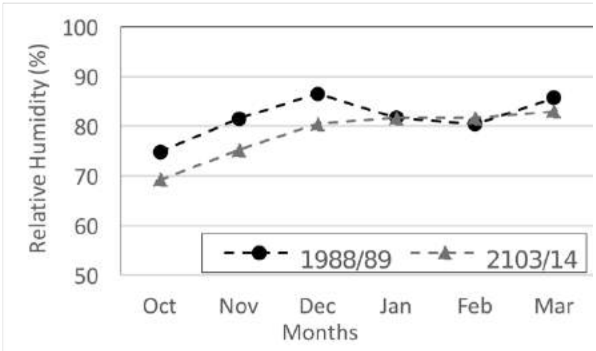


Figure 5. Mean monthly temperature and humidity during the study periods

In 1988/89 a total of relevant 3011 thermal sensation votes (TSVs) were collected and in 2013/14 the number was 1244. Figure 6 shows a plot of coincident measured internal temperature and relative humidity for the two studies. Each point coincides with a time that the residents completed a comfort vote that indicated acceptable conditions or a preference for no-change. It can be seen that, for both studies, the greatest proportion of data points fall outside of the 'traditional' comfort zones. A two-dimensional two-sample Kolmogorov-Smirnov test shows that the two data sets are significantly different (p<0.01). The mean internal temperature of all houses over the period in 1988/89 was 30.2 °C (SD=1.9) for a mean external temperature of 29.1 °C while the mean internal temperature in 2013/14 it was slightly cooler at 29.7 °C (SD=2.0) for an external temperature mean of 28.3 °C.

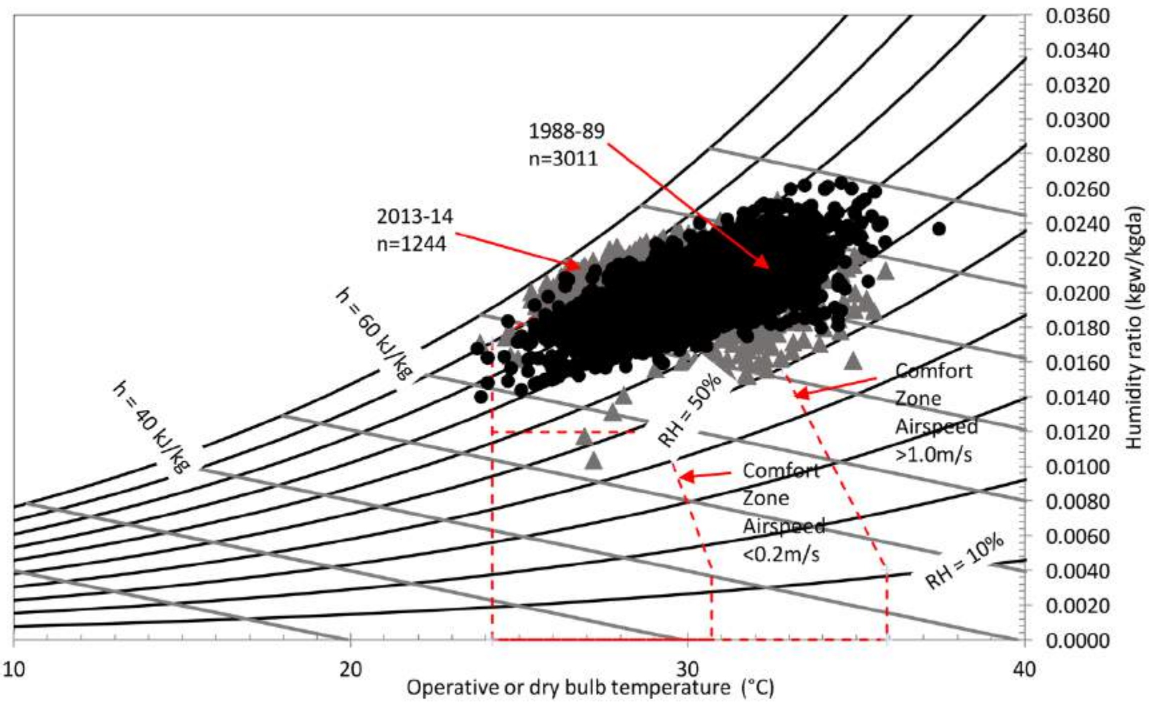


Figure 6. Indoor environmental conditions at the times that thermal comfort vote surveys were completed compared with the ASHRAE 55-2013 acceptable comfort zone for conditioned spaces (0.5 & 1.0 clo zones combined)

3.2. Airspeed

In the 1988/89 study airspeed was not directly measured as it was in 2013/14. In 1988/89 occupants were asked to record their perception of air movement with a three-button choice at the time of voting. In the CVL instruction manual the buttons were described as representing: No Air Movement, Slight Air Movement or Breeze. Detailed spot airspeed measurements determined that these descriptors could be associated with the ranges <0.1m/s, 0.1-0.5m/s and >0.5m/s. Using the median of these range values, the mean airspeed at time of voting was calculated as 0.34m/s.

In the 2013/14 study the airspeed was measured directly by the logger. The average recorded wind speed over the wet and build-up periods was 0.26m/s.

Taking into account the variations of airspeed within a room there is likely no substantial difference in conditions experienced by the occupants in the two studies. It was also observed that nearly all houses had installed ceiling fans that operated almost continuously throughout the day and seasons. During interviews residents reported that air movement was not only important for thermal comfort but also was imperative to reduce the growth of mold especially during the humid periods of the build-up and wet.

3.3. Clothing

Information on the clothing levels of occupants were collected in both studies. In 1988/89 occupants indicted their level of clothing at the time of voting via a three-button choice on the CVL. The labels on the clothing buttons described the proportion of the body covered as a proxy for estimating the level. These were designated as: ¼ covered, ½ covered and ¾ covered. The meaning of these descriptions was further explained in the CVL instruction manual. For example, ½ Covered – about ½ of your body is covered with light clothes e.g. shorts, T-shirt and thongs; or light summer dress, sandals & bare legs. The percentage of votes in each category are shown in Figure 7. In subsequent analysis these were assigned clothing levels as 0.1clo, 0.25clo and 0.6clo.

In 2013/14 clothing level data was also collected at time of voting. In this case four diagrams of different clothing arrangements described as: Very Light, Light, Medium and Heavy, were presented to the occupants. The percentage of votes in each category are shown in Figure 7. In subsequent analysis these were assigned clothing levels as 0.04clo, 0.35clo, 0.72clo and 1.0clo.

Calculating the mean clothing levels from this data shows very little difference between the two studies: 0.26clo in 1988/89 and 0.29clo in 2013/14. Within the error range of assumptions, the clothing levels show no adaptation in the interval between the studies.

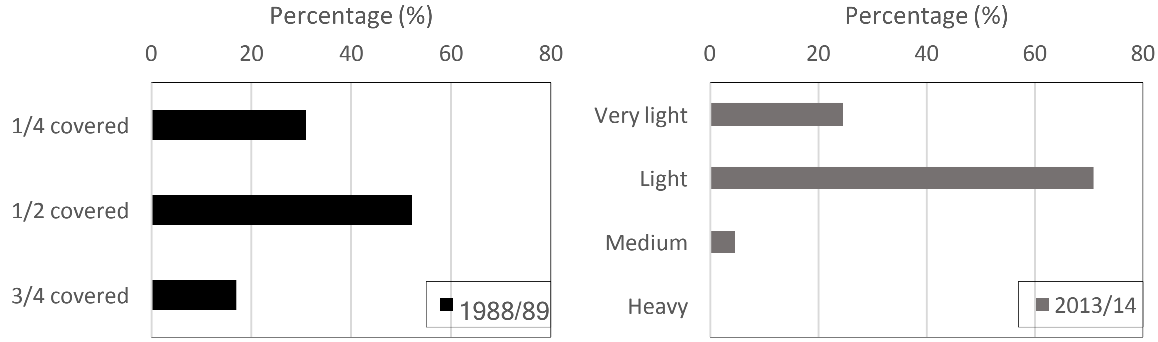


Figure 7. Clothing levels at the time of completion of the thermal comfort vote surveys, both cohorts

3.4. Activity

Activity level data was also collected in both studies at the time of voting and shown in Figure 8. In 1988/89 occupants indicated their recent activity level with a three-button choice on the CVL. These buttons were designated as: Sitting (Relaxed), Sitting (Active) and Moving Around. Sitting (Active), was described in the instructions as "could be having dinner, or sitting having a lively chat with friends". In subsequent analysis these were assigned the activity levels of $60W/m^2$, $70W/m^2$ and $85W/m^2$.

In the 2013/14 study the voting form showed diagrams of four activity levels that represented Relaxing, Sitting, Standing and Standing Active. These were associated with metabolic rate values of $46W/m^2$, $58W/m^2$, $81W/m^2$ and $115W/m^2$.

Calculating the mean metabolic rates from this data shows very little difference between the two studies: $75W/m^2$ in 1988/89 and $78W/m^2$ in 2013/14. Taking into account the possible error of assumptions, activity levels appear not to have changed.

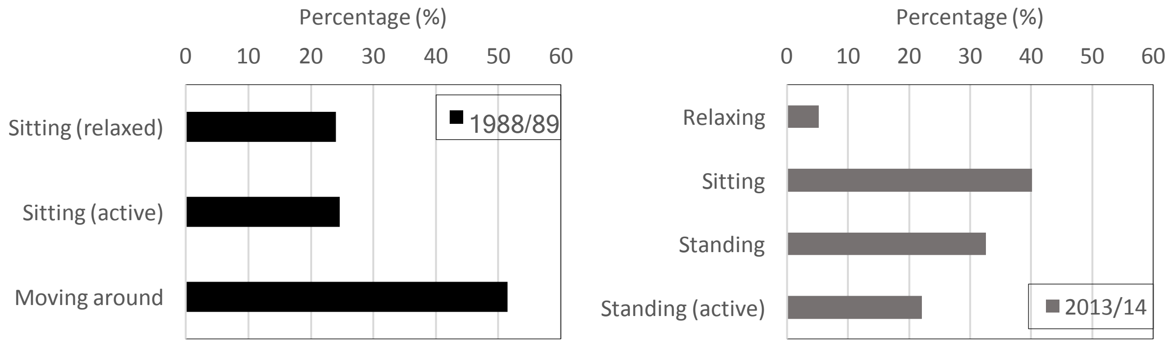


Figure 8. Recent activity levels at the time of completion of the thermal comfort vote surveys, both cohorts

4. Comfort scales

A challenge for the comparative analysis of the two studies is presented because of the different thermal sensation scales used. Figure 9 giving the percentage of votes at each interval shows, however, that the two scales appear to behave in a similar way. A closer examination however shows that there are subtle differences between the DISC and ASHRAE scales. For example, the width of the 3 central categories in the DISC scale is 3.5 while for the ASHRAE scale it is 2.8 (Figure 10). A standard error analysis shows that in each case only the three central categories are well defined.

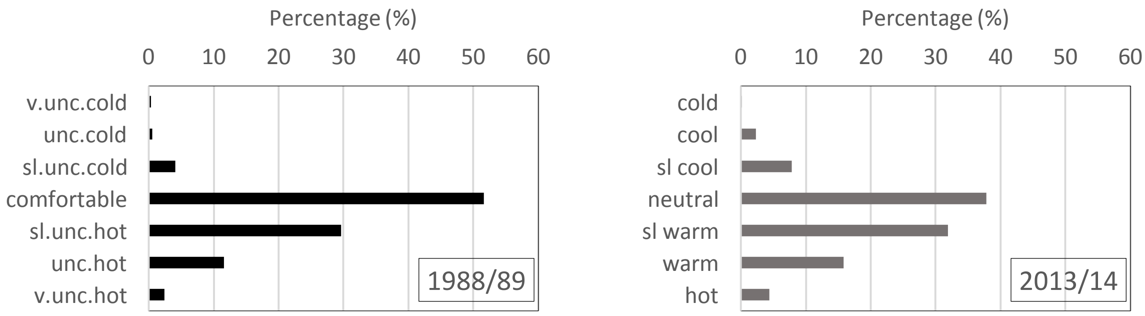


Figure 9. Thermal sensation votes for both studies

Humphreys et al. (2016, p 137) suggest a way they term *"the method of successive categories"* for comparing the behaviour of different scales as well as re-numbering scales to allow direct comparisons to be made. Using this technique and calculating the probit values from the cumulative portion of votes in each category the scales have been adjusted to allow direct comparison. The problems of comparison are diminished by "jiggling" the values attributed to the category centres, centring the central category on zero and adjusting the residual standard deviation of each scale to its original value. After applying these operations, the width of the central category is DISC 1.39 ±0.015 and ASHRAE 1.21 ±0.020 and for the three central categories they are DISC 3.34 ±0.046 and ASHRAE 3.43 ±0.051 (Table 1). In each case they are now sufficiently close for direct comparisons to be made. In all subsequent analysis the raw thermal sensation votes (TSV) are adjusted to the revised values.

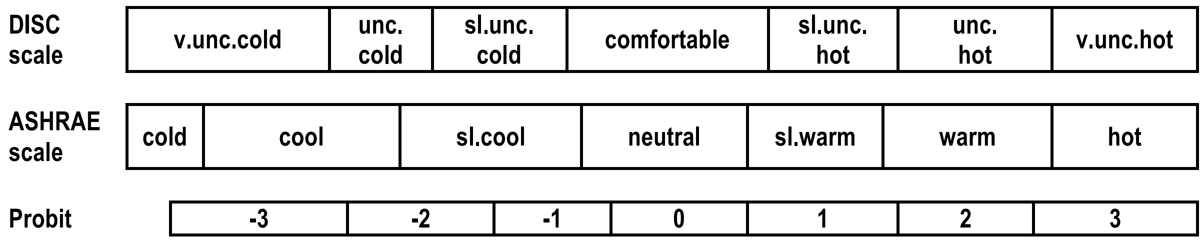


Figure 10. Comparing the category widths and offsets for the DISC and ASHRAE revised scales

Table 1. Renumbered scale values

Original scale	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**
DISC (1988/89)	-2.94	-2.288	-1.529	0	1.258	1.6	2.489
ASHRAE (2013/14)	-4.566	-2.969	-1.347	0	1.065	1.485	2.7

5. Results

In comparing the 1988/89 and 2013/14 studies the thermal expectation of 'physical comfort' can made on four measures – external versus indoor temperatures, thermal acceptability, thermal sensitivity and thermal neutrality. These criteria are also central to the adaptive thermal comfort concept.

5.1. Method of Analysis

Thermal comfort is not a tidy phenomenon and people can express different sensations of hot or cold at the same temperature as can be seen in Figure 11 which shows the 'raw' votes versus the measured indoor temperature for the 1988/89 subjects. For analysis in this paper we bin the temperature observations into half-degree (K) increments. While not affecting the results, this simplifies the process of discovering underlying statistically valid relationships. Weighted regression models are fitted to the relevant data. As the indoor dry bulb (Tdb) was the only temperature measurement available from the 1988/89 study this was used as the heat index for both studies. Preliminary analysis of the 2013/14 data showed that the regression coefficients of various heat indices (eg *Tbd, Tglb, Tmrt, Top*) with TSV showed little variation (results not shown). The indoor dry bulb temperature could therefore be used as a sufficient proxy for the operative temperature. All analysis is performed at the house/building level and results aggregated by a meta-analysis of the individual results. Any building analysis that failed to reach statistical significance at $p<0.05$ was dropped from the meta-analysis.

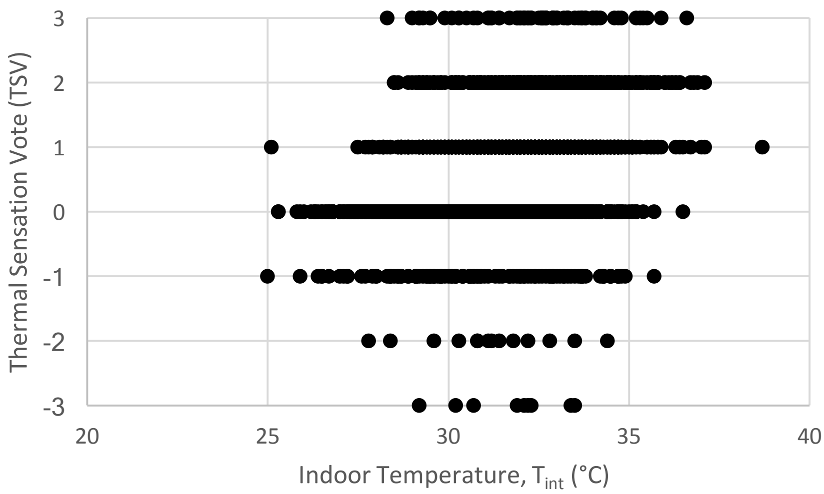


Figure 11. Thermal Sensation Votes vs Indoor Temperature, 1988/89 Study

5.2. External versus indoor temperature

At each vote time the prevailing mean external temperature has been calculated as the running temperature according to the ASHRAE 55-2013 equation I-1 with α=0.6 (ASHRAE, 2013). A plot of this binned external temperature versus the corresponding internal temperature, as seen in Figure 12, shows no significant difference between the slope (t=1.93, p=0.07 and intercepts (t=1.86, p=0.08) of the two weighted regression lines of the two studies. This is as expected because both groups of houses are very similar, operating with natural ventilation. The slightly warmer indoor conditions recorded during the 2013/14 study when the external temperature exceeds around 28°C could be explained by 'improved' house designs since the introduction of 'Energy Efficiency' provisions to the Northern Territory Building Code in 2003. These provisions included roof thermal insulation, and shading. Several households in the 2013/14 study commented that their houses were warmer in hotter weather following the retrofitting of bulk thermal insulation in the ceiling.

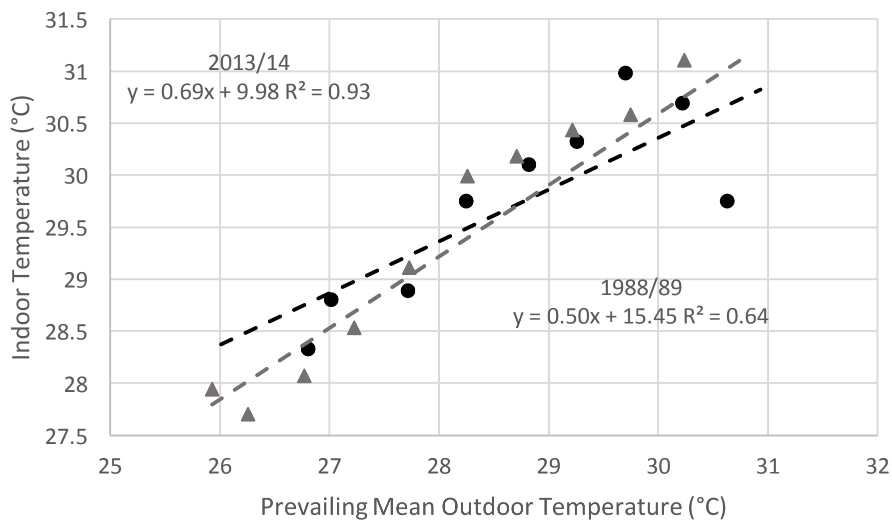


Figure 12. Plot of Prevailing outdoor versus Internal temperature at time of TSV voting

5.3. Thermal acceptability

Acceptable indoor conditions are achieved when the TSVs are in the three central categories. If occupants are completely adjusted to the thermal environment then the plot of indoor temperature against the acceptable indoor temperature would be a line of unit slope, that is, on average the acceptable temperature would equal the indoor temperature. Figure 13 shows the weighted regression lines for the indoor temperature binned at 0.5K versus the acceptable temperature. For the 1988/89 the slope is 0.92 with a squared correlation coefficient of 0.93 and a standard error of 0.05. For the 2013/14 cohort the slope is 0.99 with a squared correlation coefficient of 0.95 and a standard error of 0.14. The slope of the 2013/14 plot shows that the occupants are slightly better adjusted compared with the 1988/89 cohort but there is no significant difference between the two studies. The weighted regression plots of prevailing mean outdoor temperature binned at 0.5K intervals against the acceptable indoor temperature, as shown in Figure 14, shows a significant difference between the two studies (t-value=6.12, p=0.0).

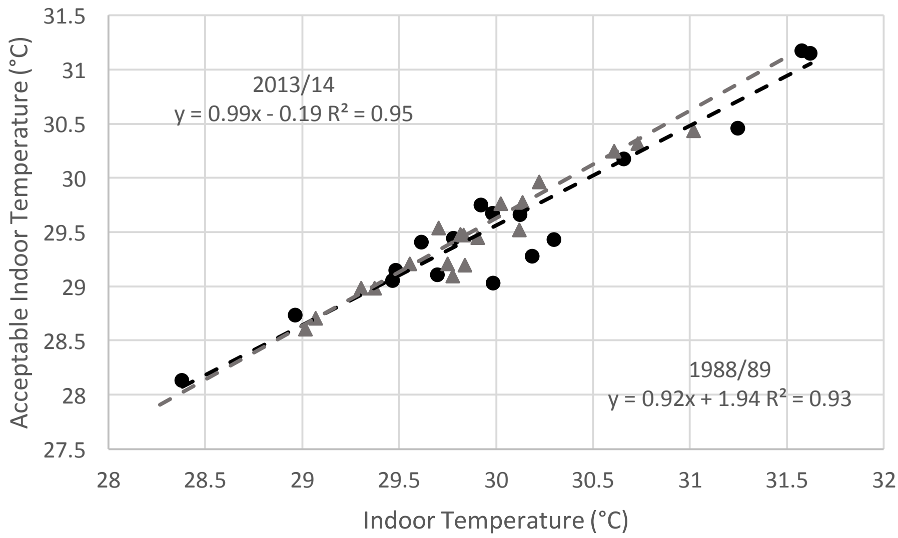


Figure 13. Indoor temperature binned at 0.5K versus Acceptable indoor temperatures for the two studies

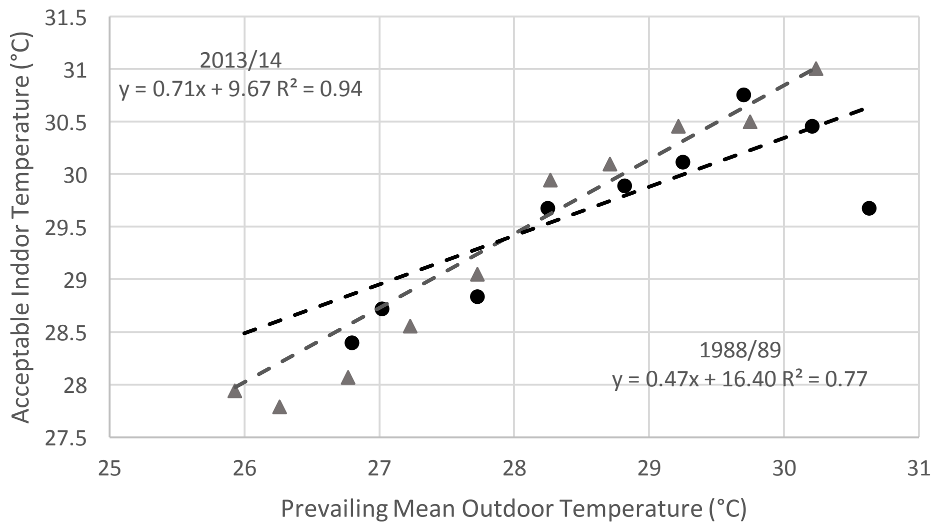


Figure 14. Prevailing mean outdoor temperature versus Acceptable indoor temperature i.e. for 1.5<TSV<1.5

The proportion of acceptable votes was calculated for 0.5K bins of indoor temperatures for the two studies and are shown in Figures 15 and 16. A quadratic curve is fitted weighted by the number of samples falling within each of the bins.

The temperature that corresponded to maximum acceptability in 1988/89 is 27.8 °C while in 2013/14 the corresponding temperature is slightly cooler at 27.3 °C. The flatter curve for the 1988/89 cohort supports the hypothesis given in Figure 14 that the older cohort are more accepting of higher temperatures.

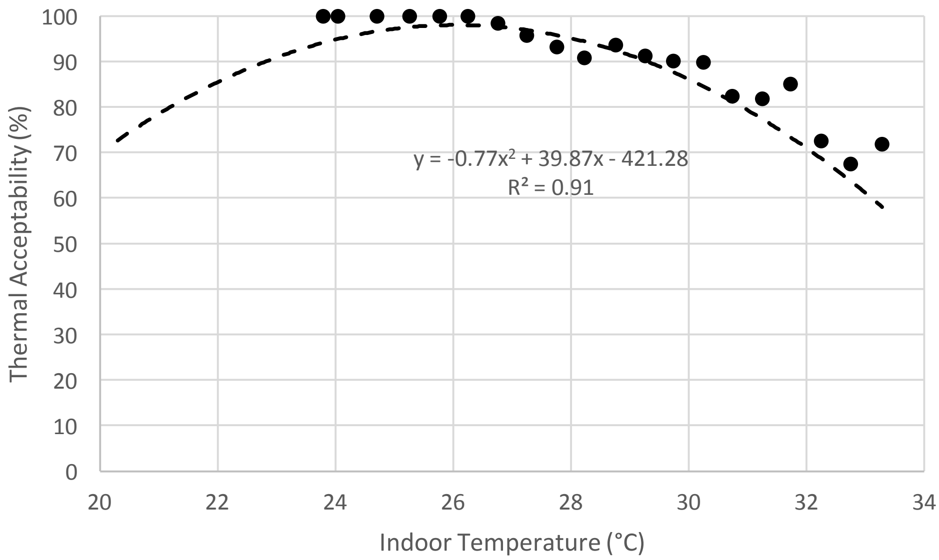


Figure 15. Thermal acceptability for the 1988/89 cohort. Each data point represents the proportion of subjects voting in the central three categories of the 7-point scales

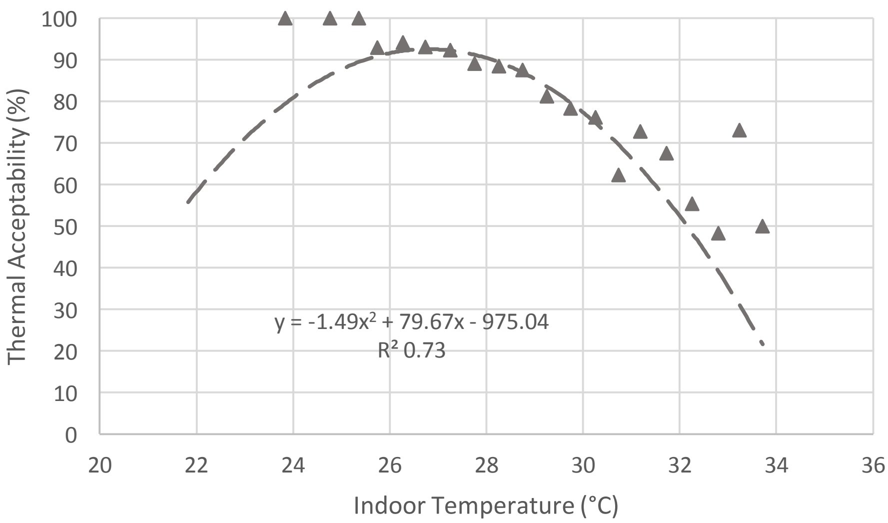


Figure 16. Thermal acceptability for the 2013/24 cohort. Each data point represents the proportion of subjects voting in the central three categories of the 7-point scales

5.4. Thermal sensitivity

The thermal sensitivity of occupants for the two studies was assessed by plotting the internal temperature against their TSVs. Figure 17 shows the weighted regression lines for internal temperatures binned at 0.5K. The gradient of these plots is interpreted as being inversely related to the occupant's thermal adaptability, the greater the slope the more sensitive are they to temperature changes. Calculating the probability values for the difference between the two slopes shows that they are significantly different (t=2.92, p=0.00). Following this logic, the 2013/14 cohort of households are more than 50% more sensitive to temperature variations compared with the 1988/89 group. Solving for the internal temperature at TSV equal to zero, that is the overall neutral temperature, for 2013/14 group is 27.8 °C while the 1988/89 cohort is slightly lower at 27.2 °C. There is no statistically significant difference between these values.

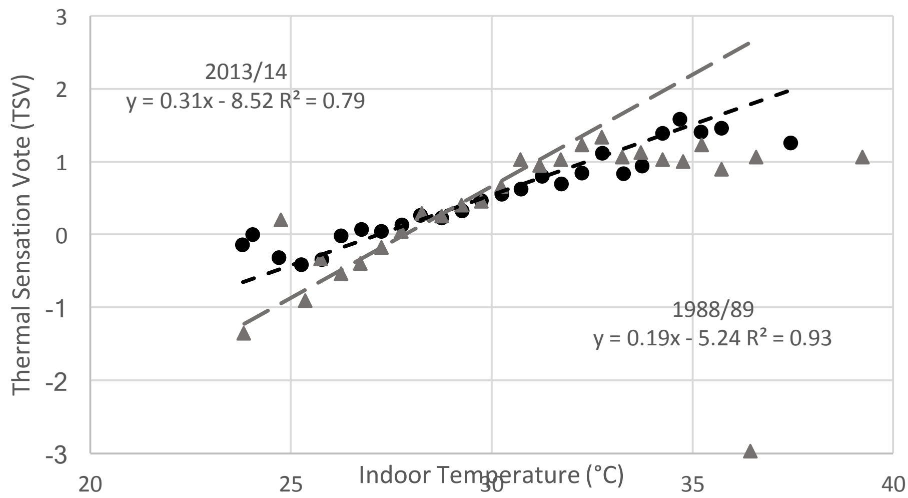


Figure 17. Thermal sensation votes (TSVs) regressed on the Internal temperature, Tint. Regression line is weighted by the number of TSVs falling in each of the half-degree temperature bins

The cohort 80% acceptable temperature ranges derived from the curves shown in Figures 15 & 16 are given in Table 2. This indicates that the comfort range of the 2013/14 cohort is reduced by 3.9K. This result is consistent with the slopes of the regression lines given in Figure 17 and can be compared to the ASHRAE adaptive model's 80% acceptability range of 7K. Also shown in Table 2 is the comfort range determined by the ASHRAE 55 adaptive model method of solving the regression equations shown in Figure 17 for TSV of ±0.85. (de Dear & Brager, 1998). The 80% acceptable temperature range for the 1988/89 cohort however corresponds to group mean thermal sensation vote of ±0.93 while for the 2013/14 cohort the value is ±0.88. The assumption from climate chamber studies that the PPD reaches 20% at a consistent group mean thermal sensation vote of ±0.85 does not hold for these field studies.

Table 2. Comfort range widths for 80% thermal acceptability

Cohort	80% thermal acceptability derived from curves (K)	ASHRAE Method (i.e. TSV ± 0.85) (K)
1988/89	9.7	8.8
2013/14	5.8	5.5

5.5. Neutral temperature

To examine the essential concept of adaptive comfort, that the indoor neutral temperature is a function of the prevailing mean outdoor temperature, the TSVs for the two studies were disaggregated by individual households. The neutral temperature was calculated for each household of the two cohorts and then matched to the appropriate prevailing outdoor temperature that had been binned at 0.5K intervals. A household was omitted from this meta-analysis if the neutral temperature failed to meet 95% significance or if the result was an outlier as determined by the method of Cook's distance. A total of 13 of the 17 1988/89 households were valid and 15 of the 19 2013/14 households were valid. Weighted regression lines were determined for each of the studies, as shown in Figure 18.

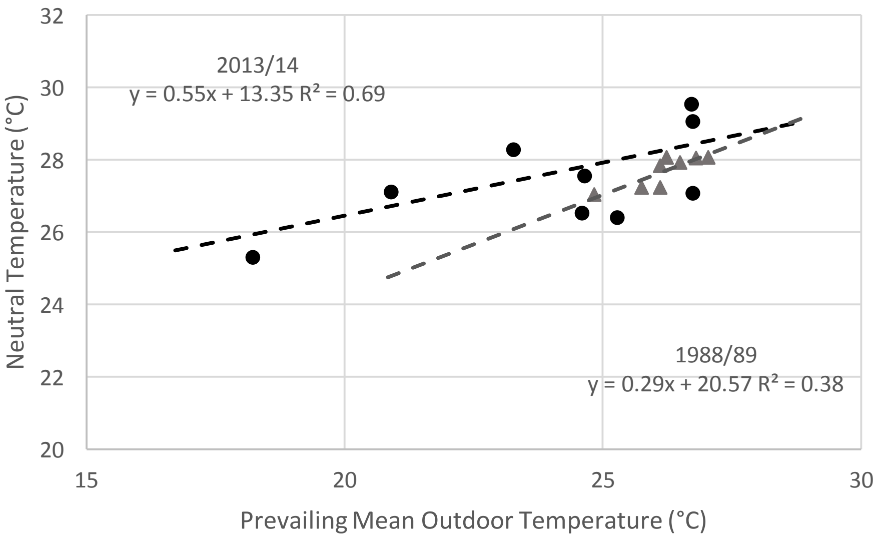


Figure 18. Relationship between cohorts' Neutral temperature (T_n) and Outdoor temperature (T_{rm})

A t-value test to examine the significance of the difference between the two slopes shows that they are not significantly different (t=1.26, p=0.22). This means that over the 25-year period the relationship between the outdoor temperature and the neutral temperature has not significantly altered. This gives some confidence in applying a general tenant of adaptive comfort theory, i.e. the neutral temperature can be related to the prevailing outdoor conditions.

6. Discussion

This paper set out to examine what changes in thermal expectations, if any, might have occurred for residents in naturally ventilated houses in Darwin, Northern Territory over a 25-year period. Darwin has become a very different place in the period but a comparison of the two studies in terms of clothing levels, activity rates of residents and air speeds observed in the houses indicates very similar comfort expectations for these cohorts. Not surprisingly the relationship between the external temperature and internal temperature, and therefore acceptable conditions for these naturally ventilated dwellings was found to be similar. While the mean internal temperature for the recent cohort was slightly lower in line with the mean external temperature conditions, the excess of temperature (that is, $\bar{T}_{int} - \bar{T}_{ext}$) was 0.4K higher. As noted above anecdotal evidence from resident interviews suggests this finding is a direct result of the introduction into the National Construction Code of mandatory energy efficiency provisions inappropriately applied to these types of houses.

The neutral temperature of the two cohorts as a function of the prevailing external temperature (Figure 18) was not found to be significantly different. However, significant differences in the cohorts' thermal sensitivity and acceptance have been observed. As seen in Figure 17, the recent cohort was found to be slightly better adapted to the indoor temperature while being more sensitive (or less tolerant) to indoor temperature changes. Related to the prevailing mean external temperature as seen in Figure 14, the two cohorts showed a significant difference in relation to the indoor acceptable temperature (and this was significantly different to the corresponding neutral temperature). At higher external temperatures, that is above around 28 °C, the recent cohort was more accepting but at the same time, the range of satisfactory temperature conditions around the mean at the 80% level, is 1.8K narrower than the earlier cohort.

We can hypothesis the reasons for these observations. As suggested in the opening paragraphs exposure to air-conditioning outside of the house, e.g. in offices, shopping centres, and cars may be changing people's perceptions and behaviours in relation to the 'natural' conditions of a free-running house. The findings are consistent with this proposition; that the 2013/14 occupants are more sensitive to higher temperature conditions, but also conversely more tolerant because they do get relief in air-conditioned places.

Other reasons however could also be contributing to the results. Humidity, often discussed as a contributing factor to thermal comfort in tropical regions, is a confounding factor. While overall the 'external' humidity taken from the Bureau of Meteorology data recorded at the airport was lower during the 2013/14 study, the 'internal' humidity was, on average, higher. This is likely due to the noticeable increase in vegetation planted around houses in order to provide shade. Further investigations would be required to address this issue.

Discussions with long term Darwin residents have suggested several other possible explanations:

- Residents are becoming increasingly desensitised to the natural climate not only by exposure to air-conditioning but also by the installation of swimming pools. 45% of the 2013/14 study houses had swimming pools which residents reported they used regularly to cool off; perhaps making them more tolerant of higher temperatures.
- Differences in clothing. Traditionally clothing was made with cotton fabrics but more recently synthetic fabrics have become more widely used. Many synthetic fabrics are not suitable for tropical wear because of their higher water vapour resistance and would tend to increase discomfort. Changing social norms, however, have meant that people are likely to be wearing less clothing at home.
- Along with the general population, the proportion of adults overweight in the Northern Territory has increased from around 40% in the mid-1980s to a current level of over 60%. People with a higher Body Mass Index may be less tolerant to higher temperatures at higher humidity levels.

Again, further research would be required to investigate these issues.

An important point to clearly emerge from this analysis can be seen by comparing Figures 14 and 18, i.e. that acceptable temperatures differ from neutral temperatures. Combing the Figures 14 and 18 in Figure 19 shows that households are prepared to accept conditions that are at times more than 1.5K above the neutral temperature and about 3K above the ASHRAE 55 Standard adaptive comfort model. In this situation a judgement concerning the satisfactoriness of a house design based on the assessed neutral temperature or the adaptive comfort equation of ASHRAE 55 would not be appropriate as it would significantly mis-estimate the conditions that these cohorts of householders judge as acceptable.

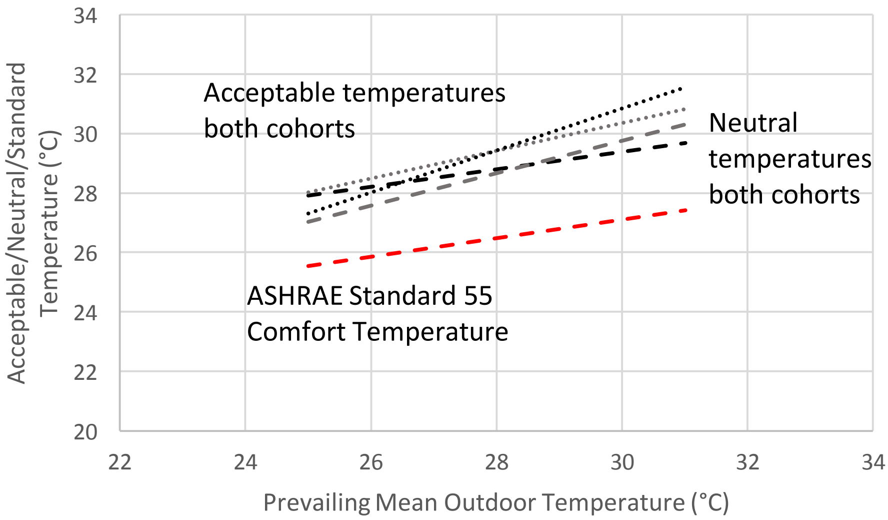


Figure 19. Acceptable and Neutral temperatures compared for both studies, together with the ASHRAE 55 adaptive comfort equation

7. Conclusions

An examination of the thermal expectations of two cohorts of households in naturally ventilated dwellings in Darwin, Northern Territory some 25-years apart show little or no change in the context variables examined. These findings support the proposition that for these occupants, expectations are driven by a desire to live with the local environment and without air-conditioning. With a relatively consistent context related to clothing levels, activity rates and air movement, the stability of the basic concept of adaptive comfort that, for free-running houses, the acceptable indoor conditions vary with the indoor temperature and therefore the prevailing mean outdoor temperature (Humphreys, 1978) has been confirmed by the analysis presented above. However, fundamental issues for application of the concept have been exposed. First, in some circumstances, temperature preferences may be other than neutrality, secondly, the acceptable conditions may change over time and finally, the acceptable range of temperatures may vary with time due to a variety external factors, including it is supposed exposure to air-conditioning. These issues need to be addressed by further research so that the adaptive approach to thermal comfort can be applied across all circumstances with confidence.

8. Postscript

A recent report to the Northern Territory Minister for Lands and Planning by an independent advisory body investigated *"the areas of: building regulation and its impact on climatically responsive design, with regard to flexibility and cost, and administrative process – all as they affect residential development in the Territory"*. They concluded, inter alia, that *"Thermal comfort is both subjective and empirically measured. However, it is not referred to directly in the Code, including in the Energy Efficiency provisions. Not everyone wants air-conditioning, including 'thermal mavericks' who live outside comfort norms, preferring free-running dwellings (without mechanical heating or cooling). Thermal comfort is subjective; but it is also researched empirically and incorporated in thermal modelling and engineering techniques to* *deliver targeted internal temperatures in buildings."* The report calls for a re-calibration of the comfort criteria employed in NatHERS for dwellings designed to be naturally ventilated.

The psychrometric chart Figure 6 above shows the comfort zone criteria incorporated into the present NatHERS energy efficiency software for the assessment of residential buildings in the Darwin climate zone. Delsante (2005) describes the method of determining these comfort zones based on the Auliciems (1983) adaptive relationship for all buildings, $T_n = 17.6 + 0.31T_m$, where T_n is the neutral temperature and T_m is the mean monthly outdoor air temperature. The 90% acceptability upper limits of comfort are set as (neutral temperature + 2.5K + ΔT), where, 2.5K is half the 90% acceptable bandwidth (ASHRAE, 2013), $\Delta T = 6*(v - 0.2) - 1.6*(v - 0.2)^2$, where v is the indoor air speed (m/s)). ΔT represents the cooling effect of air movement (Szokolay, 2000). In Figure 6 for both studies combined only 64% of acceptable/no-change votes lay within the extended comfort zone yet 100% of votes shown where considered by the occupants as satisfactory. The result is that dwellings designed as effectively free-running and considered satisfactory by the occupants must be assessed as fully air-conditioned to demonstrate compliance with the Code (i.e. via NatHERS).

As pointed out above, the essential error in the NatHERS methodology is to assume that acceptable conditions in these cases are associated with the neutral/comfort temperature defined such as the ASHRAE 55 Standard. If, however the upper limit is set at (acceptable temperature + 2.2K + ΔT) where the acceptable temperature is taken as the average of the two studies as shown in Figure 13, $T_{acc} = 13.0 + 0.58T_m$ and 2.2K is half the 90% acceptable bandwidth averaged from both studies, a different outcome is achieved that matches the empirical evidence. As shown in Figure 20, it would mean that 86% of all acceptable votes would be assessed as being within the "comfort" zone and the dwelling would be considered satisfactory.

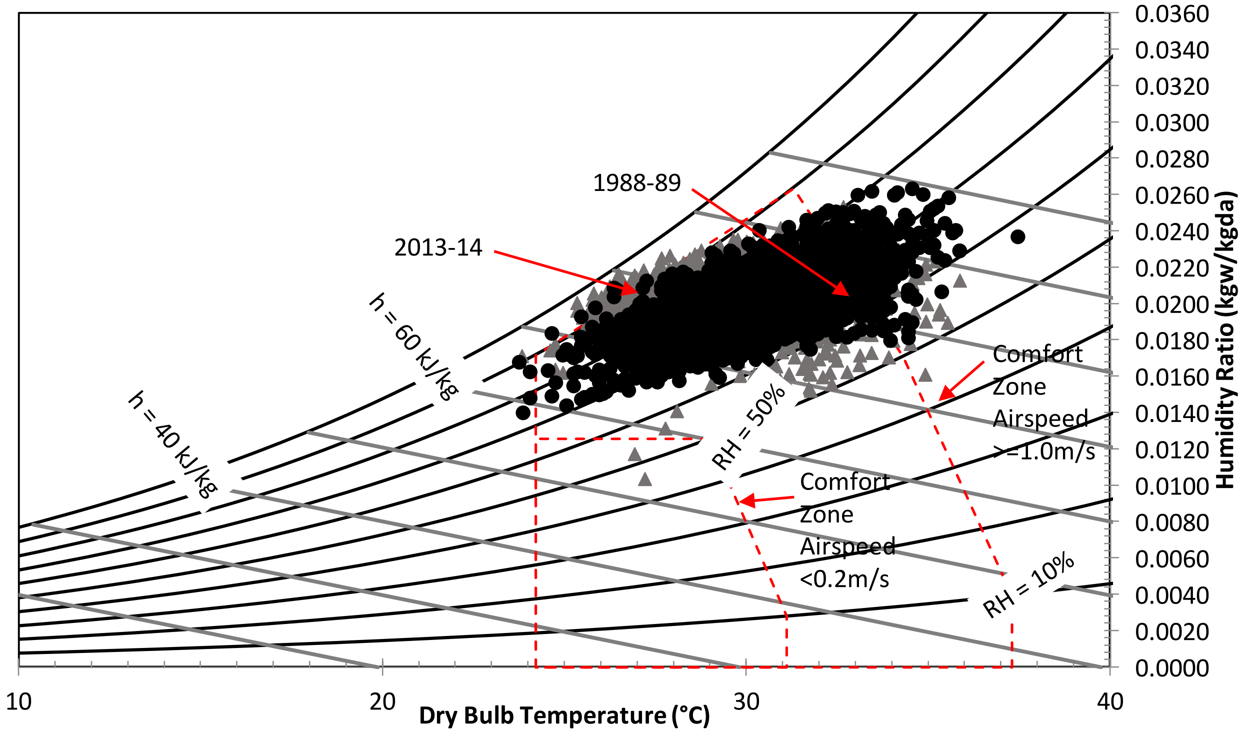


Figure 20. Indoor environmental conditions at the times that thermal comfort vote surveys were completed compared acceptable "comfort" zone extended based on data from 1988/89 and 2013/14 studies.

9. Acknowledgements

The authors are grateful for the assistance of the many Darwin households that participated in these studies. Part of the 2013/14 research was supported by funding from CSIRO.

10. References

ASHRAE (2013) ANSI/ASHRAE Standard 55-2013: Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc, Atlanta, US.

Auliciems, A. (1981). Towards a psycho-physiological model of thermal perception. *International Journal of Biometeorology, 25*, 109-122.

Auliciems, A. (1983). Psycho-physiological criteria for global thermal zones of building design. Biometeorology, No.8, Part 2, Supplement to Vol. 26 (1982), International Journal of Biometeorology, 69-86.

Australian Bureau of Statistics (ABS). (2012) 4670.0 – Household Energy Consumption Survey, Australia: Summary of Results, 2012. LATEST ISSUE Released at 11:30 AM (CANBERRA TIME) 24/09/2013 First Issue, http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by%20Subject/4670.0~2012~Main%20Features~Summary%20of%20Findings~13

Australian Bureau of Statistics (ABS). (2014) 4602.0.55.001 – Environmental Issues: Energy Use and Conservation, Mar 2014. Latest ISSUE Released at 11:30 AM (CANBERRA TIME) 03/12/2014, http://abs.gov.au/AUSSTATS/abs@.nsf/Lookup/4602.0.55.001Main+Features1Mar%202014?OpenDocument

Brager, G., & de Dear, R. (2003) Historical and cultural influences on comfort expectations in *Buildings, culture and environment: Informing local and global practices*. Blackwell Publishing.

Delsante, A. E. (2005). Is the new generation of building energy rating software up to the task? - a review of accurate. Paper presented at the ABCB Conference 'Building Australia's Future 2005', Surfers Paradise, QLD. Online. Available: http://www.energyinspection.com.au/content/Accurate-Reviewer-s-Guide.pdf (Dec 2017)

Chappells, H., & Shove, E. (2005) Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment. Building Research and Information, 33(1), 32-40.

Fanger, P. O. (1972). *Thermal Comfort: analysis and applications in environmental engineering*. New York: McGraw-Hill Book Co.

Gagge.A.P. (1985) Thermal sensation and comfort in dry humid environments. Proc of Conference CLIMA 2000, Copenhagen, pp 77-82

Harris, P. N., & Welke, A. C. (1982). Punkahs and Pith Helmets: Good Principles of Tropical Housing Design. Darwin: Troppo Architects.

Harris, P. (2016) Report to Minister for Lands and Planning: Review Of The Domestic Building Code In The Northern Territory, Domestic Building Code Review Group, Darwin, NT.

Humphreys, M. A. (1978). Outdoors Temperatures and Comfort Indoors. *Building Research and Practice, 6*, 92-105.

Kim, J., De Dear, R. J., Parkinson, T., Candido, C., Cooper, P., Ma, Z., & Saman, W. (2016). *Field Study of Air Conditioning and Thermal Comfort in Residential Buildings.* Paper presented at the 9th Windsor Conference: Making Comfort Relevant, Cumberland Lodge, Windsor, UK.

McIntyre, D.A. 1980. "Design requirements for a comfortable environment", Bioengineering: Thermal Physiology and Comfort Eds: Cena, K.; and Clark, J.A., Amsterdam: Elsevier. pp.157-168.

Humphreys, M., Nicol, F., & Roaf, S. (2016). *Adaptive Thermal Comfort: Foundations and Analysis*. Oxon, UK: Routledge.

Szokolay, S. V. (2000). Dilemmas of Warm-Humid Climate House Design: Heavy vs. Lightweight + Cooling Effect of Air Movement. Proc. PLEA 2000, Cambridge, UK, 144-149.

Williamson, T.J., Coldicutt, S., & Penny, R.E.C. (1991) Thermal preferences in housing in the humid tropics. Energy Research and Development Corporation ERDC No. 1: Canberra.

Woodgate, M. (2014) *Submission to White Paper on Development of Northern Australia*, Joint Select Committee on Northern Australia, Online available http://www.northernaustralia.gov.au/sites/prod.office-northern-australia.gov.au/files/files/maria_woodgate.docx *(Dec 2017)*

Light exposure effects on the perception of the thermal environment

Marije te Kulve[1], Luc Schlangen[2] and Wouter van Marken Lichtenbelt[1]

[1] Department of Human Biology & Movement Sciences, NUTRIM, Maastricht University, Maastricht, The Netherlands
correspondence email: markenlichtenbelt@maastrichtuniversity.nl
[2] Philips Lighting Research, Eindhoven, The Netherlands

Abstract: A wider range for acceptable indoor temperatures can reduce building energy consumption and may be beneficial for health. In the current study, we investigated the influence of the intensity and spectrum of white light exposure on thermal comfort and sensation. In two well-controlled laboratory studies with 35 healthy young adult females, we tested the effect of the correlated colour temperature of light (2700K and 6500K, both 55lx) and the intensity of light (5lx and 1200lx, both 4000K) on thermal comfort and sensation. The light exposures were provided during cool, neutral and warm thermal conditions. Core and skin temperatures were measured. Thermal comfort and thermal sensation were not significantly affected by the light intensity or relative correlated colour temperature. The preferred lighting conditions differed between individuals. Interestingly a significant positive correlation was found between visual comfort and thermal comfort. This result implies that visually comfortable conditions may improve thermal comfort, but individual preferences should be taken into account. The main conclusion therefore is that thermal discomfort can partly be alleviated by lighting conditions that result in a higher perceived visual comfort. Field studies are required to demonstrate the practical relevance of the interaction between light exposure and ambient temperature.

Keywords: Thermal comfort, Visual comfort, Ambient temperature, Correlated colour temperature, Light intensity

1. Introduction

Allowing larger ranges for acceptable indoor temperatures can result in a significant reduction in building energy consumption (Yang,Yan and Lam, 2014). Additionally, more variation in indoor temperature could also be beneficial for health (van Marken Lichtenbelt and Kingma, 2013). Although people adapt to mild warm or cool thermal environments, both in terms of thermal comfort and physiology (e.g. (Pallubinsky *et al.*, 2017, van der Lans *et al.*, 2013), temperature variation may result in thermal discomfort. Light exposure might be able to reduce thermal discomfort since it able to influence thermal perception via the visual and non-visual pathway.

Via the visual system, light exposure can evoke associations to a warm or cold environment. Thereby, light may result in a warmer or cooler thermal sensation and influence thermal comfort. This phenomenon is also known as the hue heat hypothesis stating that an environment lit by light toward towards the red end of the spectrum is perceived warmer as compared to the light dominated by the blue end of the spectrum (Bennett and Rey, 1972). Experimental studies show that under the same thermal condition thermal comfort was slightly higher for light with a low CCT (warm colours) (Huebner *et al.*, 2016). In a similar line of reasoning, bright light can turn on the hot emotional system, since it association with heat. Thereby it can evoke a feeling of warmth (Xu and Labroo, 2014). So, via visual perception, bright light and light rich of warm colours, may evoke a warmer sensation.

Secondly, via the non-visual system, light could influence human thermophysiology and thereby influence thermal sensation and/or thermal comfort. Several experimental studies show that evening light influences body temperatures (te Kulve *et al.*, 2016). Light in the evening can result in a higher core body temperature (CBT) and reduced heat loss (e.g (Cajochen *et al.*, 2005)). Previously we showed that also in the morning, light intensity and the CCT of light exposure can affect body temperatures (te Kulve *et al.*, 2017, te Kulve *et al.*, 2018). CBT and proximal skin temperature were higher and the distal-proximal skin temperature gradient (DPG) was larger (lower) for dim light exposure as compared to bright light. Additionally, CBT was higher for light with a high CCT (6500K) as compared to a low CCT (2700K). Distal skin temperatures and means skin temperature were not affected by the light intensity or the CCT of light. In the current article, we analysed whether these light exposures (same experimental studies) also influenced subjective thermal perception, via the visual and/or non-visual pathway.

The objective of the current study was to investigate how light exposure affects thermal perception. Therefore, dim light was compared to bright light and light with a low CCT compared to light with a high CCT. These light conditions were provided during different ambient temperatures. Subjective thermal perception and visual perception were evaluated. Skin temperature and core body temperature were measured to test whether physiological adjustments related to subjective differences between light exposure.

2. Method

Two randomized crossover studies were used to compare two light intensities (study 1) and two correlated colour temperatures (study 2) (see (te Kulve *et al.*, 2017, te Kulve *et al.*, 2018) for the results on thermophysiology and alertness). Previous to the start of the study procedures, participants provided written informed consent to participate in the study. All procedures were conducted in accordance with the declaration of Helsinki. The Medical Ethical Committee of Maastricht University Medical Centre+ approved the study protocol.

2.1. Participants

In study 1, 19 participants took part in the experiments. For study 2, 16 participants were included. Inclusion criteria were: female, generally healthy, no medication use except from oral contraceptives (mandatory), BMI between 18-25 kg/m^2, age 18-30 years old and a normal chronotype (Table 1). The inclusion and exclusion criteria were checked prior to inclusion of the study using a medical questionnaire and a chronotype questionnaire (Roenneberg and et al., 2015).

Table 1. Participant characteristics

	Study 1	Study 2	All participants	
N	19	16	35	-
Age	22.3 ± 1.9	22.2 ± 2.37	22.2 ± 2.05	years
Height	1.70 ± 0.07	1.70 ± 0.06	1.70 ± 0.06	meters
Weight	62.7 ± 5.5	62.4 ± 5.33	62.5 ± 5.96	kg
BMI	21.7 ± 1.8	21.5 ± 2.07	21.6 ± 1.94	kg/m^2
Fat Percentage	30.2 ± 3.2	27.9 ± 4.72	29.2 ± 4.02	%

2.2. Protocol

The first study was carried out to investigate the effects of light intensity and compared a dim light exposure (5lx) with a bright light exposure (1200lx). The second study was performed to compare light with a CCT of 2700K with a light of 6500K. All participants took part in the two light sessions of one study. The protocol during both studies was similar.

Participants arrived at the laboratory in the evening before the start of the experiment. They refrained from alcohol and physical activity on the day of arrival and were not allowed to eat or drink (except water) after 19:00. At arrival, the participant was guided to the respiration (climate chamber) and the measurement procedures and the questionnaire were explained. At 23:00h the lights were switched off and the participant went to bed and was allowed to sleep till 7:00h in the morning. Lights were then switched on at baseline levels (study 1: 250lx and 4000K, study 2: 5lx and 4000K). After getting up, a small breakfast was provided (55kcal) and preparations for the experiment were performed. During the experiment, participants were lying on a stretcher and wore underwear to be maximally exposed to the ambient temperature.

The baseline session started at 8:00h (Study 1) or 7:45h (Study 2) under thermoneutral conditions (29˚C) (Figure 1). After that, the experiment continued with three measurement blocks with a different ambient temperature each. All participants were exposed to a cool, neutral and warm thermal condition. The order of the cool and warm condition was randomized among participants, but was the same during the two sessions of one participant (Figure 1). During these measurement blocks the light was either dim or bright in study 1 or light with a low CCT (2700K) or a high CCT (6500K) in study 2 (Figure 2). The order of the light exposure was also randomised. Each block took 75 minutes followed by a small break of 15 minutes. From the start of the experiments onwards, body temperatures were measured continuously. The methods and results on the physiological measurements are reported in (te Kulve *et al.*, 2017, te Kulve *et al.*, 2018). Questionnaires were filled out every 15 minutes, including subjective thermal and visual perception (Figure 2).

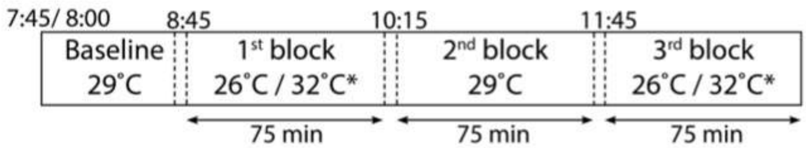


Figure 1 Study procedure of one light session of one study. * The order of the temperature conditions was randomised among participants but kept the same during both sessions of one participant.

2.3. Measurements

Thermal & visual perception

Questionnaires were used to evaluate thermal and visual perception. All subjective parameters were included in one questionnaire that was filled out every 15 minutes (as indicated in Figure 2). Thermal comfort and thermal sensation were self-reported using visual analogue scales (VAS) (NEN-EN-ISO7730, 2005, ASHRAE, 2004). The perception of the light in the room was also self-reported using two VAS's. Participants were asked to indicate how comfortable the light condition was, on a scale from "very uncomfortable" to "very comfortable".

Indoor environment

Air temperature and relative humidity were measured at one-minute intervals by means of four dataloggers (iButton, DS1923, Maxim). The iButtons were placed next to the participant at a height of 0.1 m, 0.3 m, 0.6 m and 1.1 m. The installed light system was a LED wall washer (Philips SkyRibbon IntelliHue Wall Washing Powercore). The illuminance of the lighting was confirmed with a lux meter (Testo 545) each time the lighting condition changed. The illuminance was measured in the outward direction of the optical axis at the outer surface of the participant's eye in its most usual viewing direction. The spectrum of each lighting condition was measured once using a radiospectrometer (Jeti).

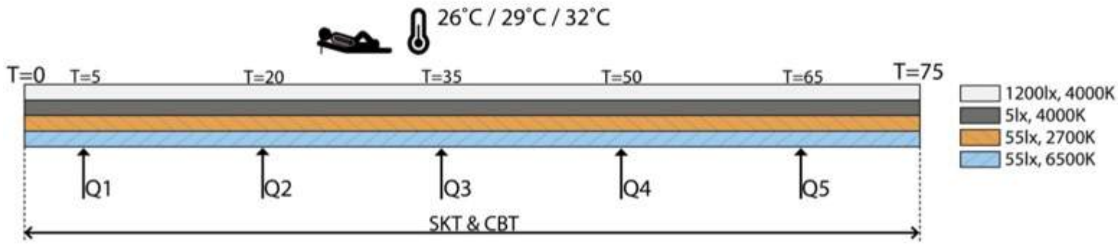


Figure 2 Schedule of the measurements during each block of 75 minutes. The questionnaires are indicated with a "Q". Skin temperatures (SKT) and core body temperature (CBT) were measured on 1-minute intervals throughout the experiment.

2.4. Statistics

The mean votes of the questionnaires were calculated from the 2nd to the 4th questionnaire, to exclude any possible disturbances at the beginning or the end of the measurement. Mixed model analyses with a random intercept were used to analyse the effect of light exposure and ambient temperature. Light and temperature and the interaction between light and temperature were the independent variables. The time of exposure was included as a covariate.

The change in visual comfort and thermal comfort was calculated for each participants' two sessions: Δ represents "bright – dim" for study 1 and "2700K-6500K" for study 2. Correlations between Δ visual comfort and Δ thermal comfort were calculated using mixed model analyses repeated for temperature. For each temperature separately, Pearsons correlations were per carried out to test the relation between Δ visual comfort and Δ thermal comfort.

All statistical analyses were performed using IBM SPSS Statistics 23.

3. Results

3.1. Indoor environment

The ambient temperature and relative humidity did not vary significantly during the different light exposures (all $p>0.05$) (Table 2). The spectra of the light exposure differed for the 2700K, 4000K and 6500K light exposure. The light intensity was 55lx during the highest and the lowest CCT and 4.1 lx during dim light and 1000lx during bright light. The intensity of 55lx was chosen in order to compare the non-visual effects of different CCT. If these effects are stimulated by a certain wavelength, we tried to avoid reaching the maximum stimulation for during conditions.

Table 2. Indoor temperatures (˚C) per temperature condition and light session (mean ± Stdev)

		Baseline		Cool		Neutral		Warm	
		Mean	*StDev*	*Mean*	*StDev*	*Mean*	*StDev*	*Mean*	*StDev*
Study 1	Dim	28.3	0.34	24.5	0.36	28.4	0.44	31.6	0.80
	Bright	28.4	0.27	24.6	0.30	28.2	0.49	31.7	0.75
Study 2	2700K	28.1	0.26	24.5	0.45	28.1	0.26	31.4	0.68
	6500K	28.2	0.31	24.4	0.37	28.2	0.35	31.4	0.56

3.2. Thermal sensation and thermal comfort

Thermal sensation was highest during the warm condition and lowest during the cool thermal condition (p<0.001). Thermal comfort was highest when participants were exposure to the neutral temperature (p<0.001), and the lowest during the cool condition (p<0.01) (Figure 3). In comparing the effect of light intensity, there was no difference in thermal comfort or thermal sensation between the dim light and bright light exposure (p>0.25). Likewise, there was no significant difference in comparing the 2700K light exposure with the 6500K light exposure (Figure 3). Additionally, there were no significant interactions between light exposure and ambient temperature.

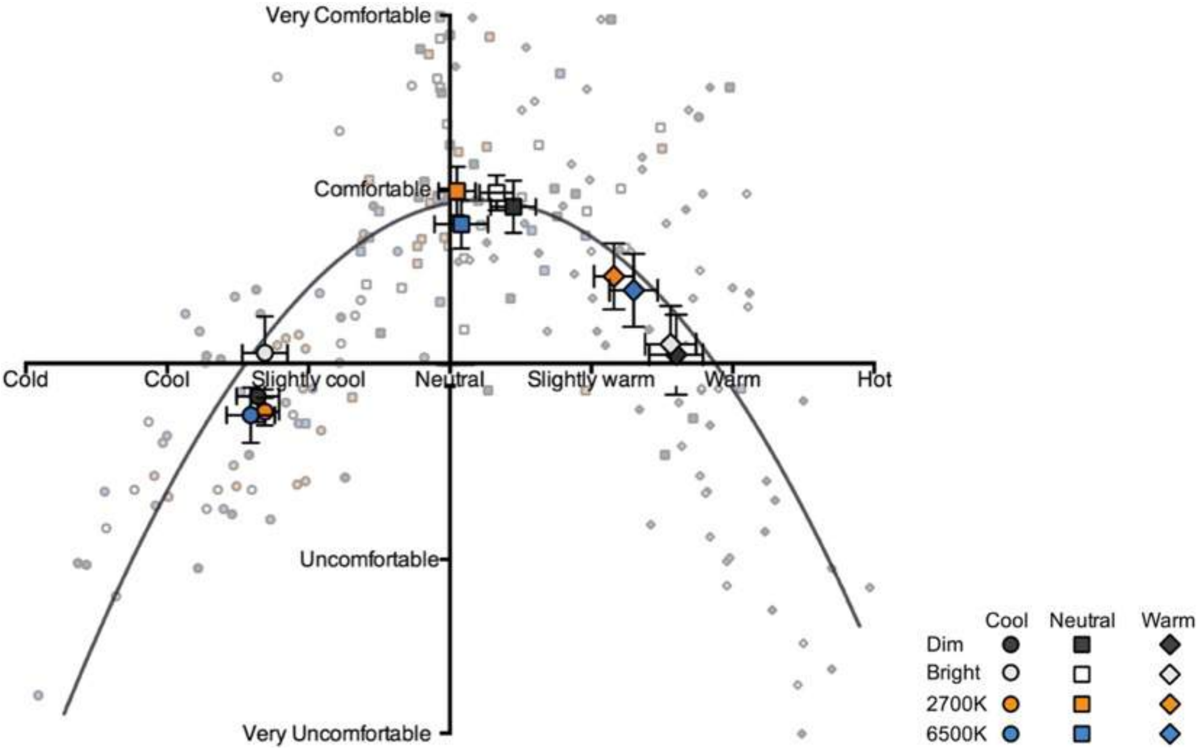


Figure 3 The distribution of the data on the thermal sensation scale (x-axis) and thermal comfort scale (y-axis) (mean ± SEM) for each temperature condition and light exposure. Individual votes are plotted in grey.

3.3. Local thermal sensation

Thermal sensation differed for the different body parts (Figure 4). The feet were perceived as the coolest and the head was perceived as warmest. However, also for the local body parts, there was no significant effects of either light intensity or the CCT of the light exposure. Taken together, there was no consistent effect of light exposure on thermal perception.

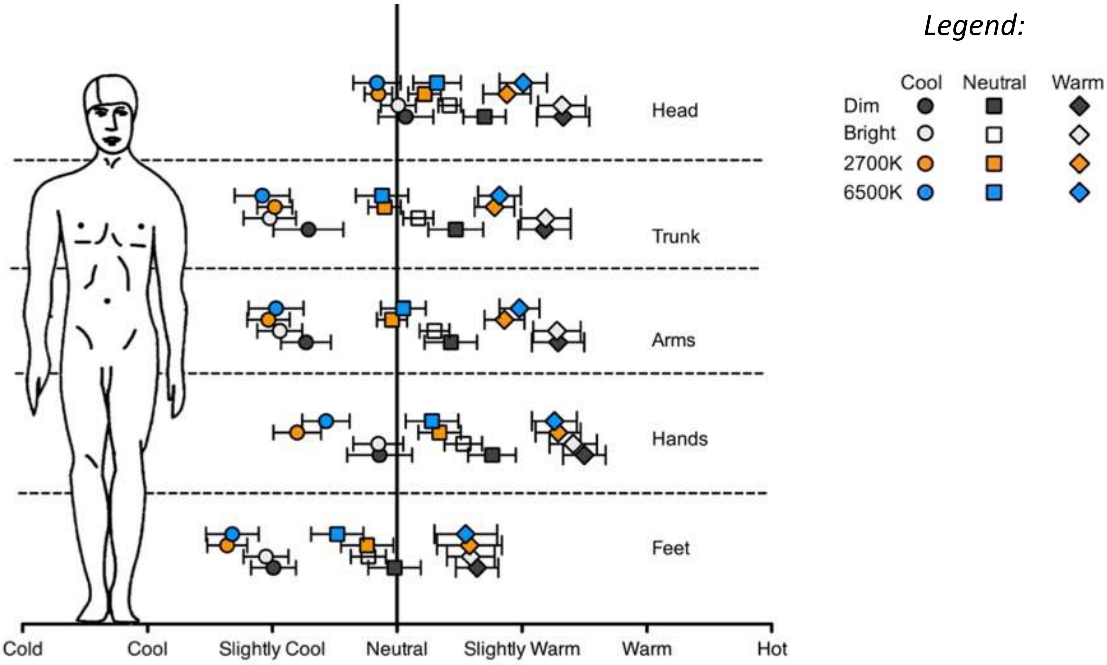


Figure 4 Local thermal sensation per temperature conditon and light session (mean±SEM).

3.4. Relation between visual comfort and thermal comfort

Visual comfort was different between the two light sessions of each study. This difference in visual comfort of each participant correlated with the difference in thermal comfort ($\Delta_{bright-dim}$ for study 1 or $\Delta_{2700K-6500K}$ for study 2) (Table 3). For the same thermal condition, thermal comfort was higher when visual comfort was higher. The correlations per temperature separately show a significant relation during the cool (Figure 5) and a trend during the warm condition (Table 3). There was no significant relation during the thermo-neutral condition (Table3).

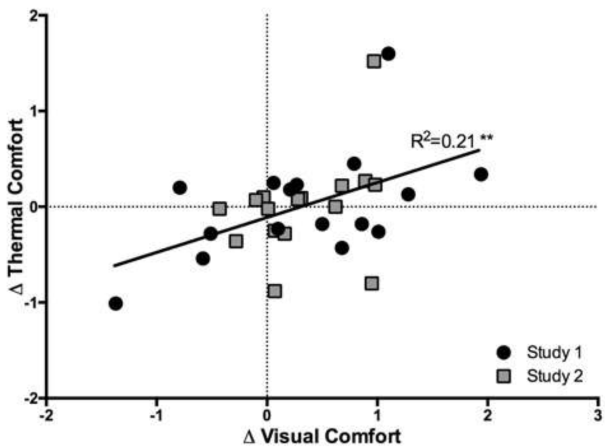


Figure 5 ∆Visual Comfort & ∆Thermal Comfort during the cool condition between each participants' two light exposures either $\Delta_{bright-dim}$ for study 1 (black dots) or $\Delta_{2700K-6500K}$ for study 2 (grey squares).

Table 3 Correlations between the change in visual comfort and thermal comfort. Results are presented for all ambient temperature conditions together (All) and per temperature condition. Correlations with a p-value <0.10 are indicated in bold.

	∆ Visual Comfort & ∆Thermal Comfort	
	$\Delta_{Bright\text{-}Dim}$ & $\Delta_{2700K\text{-}6500K}$	
	R or β	p-value
All	0.231	**0.007**
Cool	0.459	**0.008**
Neutral	0.070	0.690
Warm	0.319	**0.062**

4. Discussion

Thermal comfort and thermal sensation were not significantly affected by a specific light intensity or a specific CCT. Interestingly, visual comfort was related to thermal comfort. This result implies that visually comfortable conditions may improve thermal comfort.

Although it was observed that light exposure significantly influenced CBT, these differences were not related to differences in thermal sensation or thermal comfort. Apparently, the light induced differences in CBT and proximal skin temperatures, were too small to affect overall or local thermal sensation or thermal comfort. The relative contribution of CBT to thermal comfort was found to be equal to the contribution of skin temperatures, while changes in skin temperatures are much larger compared to changes in CBT (Frank *et al.*, 1999). This could explain why a change of 0.1˚C in CBT did not affect thermal comfort and thermal sensation.

The hue-heat hypothesis was not confirmed in the current experiment: thermal sensation was not higher for the low CCT as compared to high CCT. Besides, bright light did not evoke a higher feeling of warmth compared to dim light. A stronger association with temperature may be required to alter thermal sensation. However in the present study, the low CCT light setting and the bright light setting may have been unable to result in such associations. Light with a higher colour saturation may do so, as confirmed in previous studies (Winzen,Albers and Marggraf-Micheel, 2014, Albers,Maier and Marggraf-Micheel, 2015). Watching a cold landscape, instead of a warm landscape, can also result in a cooler sensation (Takakura,Nishimura and Watanuki, 2013).

Most interestingly, light exposure influenced thermal comfort via visual comfort. Since the light condition that was perceived as visually most comfortable was different between participants, there was not a certain intensity or CCT of light that resulted in higher thermal comfort. An earlier experiment comparing different CCT's also observed that thermal comfort was highest for the preferred light condition (Baniya *et al.*, 2016). Together this indicates that comfortable light conditions can support thermal comfort. Field studies are still required to test the practical relevance and effect size of these results. Thereby, individual light tuning or individual light settings should be provided to satisfy individual needs.

5. Conclusion

In conclusion, visual comfort and thermal comfort were associated. Higher visual comfort votes coincided with higher thermal comfort votes for the same thermal condition. Individual preference in visual conditions should be considered to obtain high visual comfort levels. The interaction between light exposure and thermal perception may allow for a larger ranger of acceptable indoor temperatures.

6. Acknowledgments

Bob Wolf and Daan Duijf are thanked for their practical work during the experiments. Paul Schoffelen and Marc Souren are gratefully acknowledged for their technical assistance. All participants are thanked for their participation. This project was funded by the STW–Philips Electronics Nederland B.V. Partnership Program 'Advanced Sustainable Lighting Solutions' (no. 12733

7. References

Albers, F., Maier, J. and Marggraf-Micheel, C. (2015) 'In search of evience for the hue-heat hypothesis in the aircraft cabin'. *Lighting Research & Technology,* 47 483-494.

ASHRAE (2004) 'Standard-55, Thermal Environment Conditions for Human Occupancy'.

Baniya, R.R. *et al.* (2016) 'The effect of correlated colour temperature of lighting on thermal sensation and thermal comfort in a simulated indoor workplace'. *Indoor and Built Environment,* 1-9.

Bennett, C.A. and Rey, P. (1972) 'What's so hot about red'. *Human Factors,* 14 (2), pp. 149-154.

Cajochen, C. *et al.* (2005) 'High sensitivity of human melatonin, alertness, thermoregulation, and heart rate to short wavelength light'. *J Clin Endocrinol Metab,* 90 (3), pp. 1311-1316.

Frank, S.M. *et al.* (1999) 'Relative contribution of core and cutaneous temperatures to thermal comfort and autonomic responses in humans'. *Journal of Applied Physiology,* 86 (5), pp. 1588-1593.

Huebner, G.M. *et al.* (2016) 'Saving energy with light? Experimental studies assessing the impact of colour temperature on thermal comfort'. *Energy Research & Social Science,* 15 45-57.

NEN-EN-ISO7730 (2005) 'Ergonomics of the thermal environment'.

Pallubinsky, H. *et al.* (2017) 'Thermophysiological adaptations to passive mild heat acclimation'. *Temperature (Austin),* 4 (2), pp. 176-186.

Roenneberg, T. and et al. (2015) *Munich ChronoType Questionnaire, English, Version 2015-01.* Available at: https://www.thewep.org/documentations/mctq/item/english-mctq-full.

Takakura, Nishimura, T. and Watanuki, S. (2013) 'Visual information without thermal energy may induce thermoregulatory-like cardiovascular responses'. *Journal of Physiological Anthroplogy* 32:26.

te Kulve, M. *et al.* (2016) 'The influence of light on thermal responses'. *Acta Physiol (Oxf),* 216 (2), pp. 163-185.

te Kulve, M. *et al.* (2017) 'The impact of morning light intensity and environmental temperature on body temperatures and alertness'. *Physiol Behav,* 175 72-81.

te Kulve, M. *et al.* (2018) 'Correlated Colour Temperature of morning light influences alertness and body temperature'. *Physiol Behav,* 185 1-13.

van der Lans, A.A. *et al.* (2013) 'Cold acclimation recruits human brown fat and increases nonshivering thermogenesis'. *J Clin Invest,* 123 (8), pp. 3395-3403.

van Marken Lichtenbelt, W.D. and Kingma, B.R. (2013) 'Building and occupant energetics: a physiological hypothesis'. *Architectural Science Review,* 56 (1), pp. 48-53.

Winzen, J., Albers, F. and Marggraf-Micheel, C. (2014) 'The influence of coloured light in the aircraft cabin on passenger thermal comfort'. *Lighting Research and Technology,* 46 465-475.

Xu, A.J. and Labroo, A.A. (2014) 'Incandescent affect: Turning on the hot emotional system with bright light'. *Journal of Consumer Psychology,* 24 207-216.

Yang, L., Yan, H. and Lam, J.C. (2014) 'Thermal comfort and building energy consumption implications – A review'. *Applied Energy,* 115 164-173.

SESSION 2

New approaches to heating and cooling people

Invited Chairs:
Richard de Dear and Atze Boerstra

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

The Effect of the Visual Cue of Mist Cooling on Perceived Thermal Comfort

Craig Farnham[1], Yuki Okazaki[1], Kazuo Emura[1], Miki Kubota[1], Jihui Yuan[1], and Md Alam Ashraful[1]

[1] Osaka City University, Department of Human Life Science, Japan
Corresponding email: farnham@life.osaka-cu.ac.jp

Abstract: On hot summer days, the cooling effect of fine water mist has been well-received. Although fine mists typically only yield an air temperature reduction of 1 – 3K, the comfort votes of those experiencing the mist are far better than expected by the PMV (Predicted Mean Vote). The transient effect of a sudden reduction in temperature may account for much of this over-evaluation of mist cooling. Yet, subjects may also be affected by an expectation that mist should feel cool and vote accordingly. In these experiments, subjects are exposed to a misting fan and a non-misting fan and asked which fan feels cooler. Unknown to the subjects, a heater increased the temperature of the misting fan air flow, producing an airflow up to 1.7K warmer than the fan without mist. Tests of over 300 subjects while varying this misted air temperature showed that on average the misting fan was perceived as cooler than the non-misting fan, even when the misting fan airflow was up to about 0.5K-0.7K warmer than the non-misting fan. It is likely that the expectation of cooling by mist significantly influences the perception of comfort. This effect should be considered in thermal comfort evaluations of mist cooling.

Keywords: Mist, evaporative cooling, PMV, expectation, thermal comfort

1. Introduction

Water mists are a low-energy method of cooling that improve thermal comfort on hot summer days. Mist droplets quickly reach the wet bulb temperature, exchanging heat with the surrounding air as they evaporate. The air temperature drops, but the humidity increases, with the ultimate limit being saturated air at the wet bulb temperature and 100% humidity. As the air approaches saturation, the evaporation rate of the droplets slows, yielding an increasing chance of undesirable wetting. Thus in practice, mists are often used outdoors or in semi-enclosed spaces, where the natural flow of air helps prevent saturation.

Evaporative cooling has been used for centuries in arid climates, where the water can evaporate quickly. The use of high-pressure nozzles to produce fine mist droplets on the order of 20 microns or less allows for evaporative cooling even in humid climates such as Singapore (Wong & Chong, 2010) without fear of wetting. In Japan, mist cooling gained attention at the 2005 World Expo in Aichi, with greatly improved thermal comfort (Yamada et al, 2006). Mists used on a train platform in summer in Japan reduced the air temperature by 1-3K, as over 80% of those experiencing it claimed improved thermal comfort in surveys (Uchiyama et al, 2008). Mists sprayed from overhead yield a natural downdraft effect. However, in outdoor use, even a slight breeze can divert the mist spray to the side before it reaches the persons below.

Combination of mist sprays with fans help to maintain a cooled flow of air in the desired direction while yielding greater improvements in comfort. Our previous experiments (Farnham et al, 2015) showed that on hot summer days, a misting fan improves thermal comfort votes by over 3 steps on a 9-step scale. Yet the temperature change (a drop of about 2 – 3K) and air speed, when applied through the standard PMV model, indicate that a much smaller improvement in thermal comfort should be expected. The transient effect of a sudden change of temperature can cause an initial over-estimation of the perceived coolness (de Dear et al, 1993). However, the fact that mist is visible, and that people may expect that a water mist on a hot day should be cool, may also affect the thermal comfort votes of those experiencing the water mist. One consideration in evaluating water mist cooling is that some portion of the improvement in thermal comfort votes may also in part be due to the expectation of cooling rather than actual cooling.

Further, those participating in the experiment might be influenced by the "good subject" effect, a desire to give the response which validates the experiment hypothesis. Subjects may seek overt or implicit cues to determine what the "correct" answer should be and give that answer; out of a desire to help the researcher, aid the progress of science, seek approval from the experimenter, or other motives (Ronsow et al, 1997). In the case of mist cooling on hot summer days, there is little mystery that the "correct" answer should be to claim that mist feels cool.

One may ask, "Is the improved thermal comfort from water mists due in part to an expectation of cooling or 'good subject' effects rather than the actual drop in temperature? Is comfort survey data of subjects experiencing cooling mists valid? How powerful is this type of effect? "

This research seeks to reveal what portion, if any, of the perceived thermal comfort of people experiencing a mist fan is due to the expectation of cooling or other psychological factors, as opposed to the actual cooling effect of the mist. This is accomplished by exposing subjects to misting fan sprays that have been secretly heated to yield no cooling effect, or even an increased air temperature, and asking them to compare that with an identical fan blowing a stream of air without mist. To what extent will subjects claim that a flow of misted air is cooler than a stream of non-misted air, even when the misted air is warmer than the non-misted air?

2. Theory

Mist cooling is an adiabatic process. The latent heat of evaporation is exchanged for the sensible heat of air temperature. The air cools, while following a constant-enthalpy line on the psychometric chart, with slight deviations due to sensible heat exchanges between water and air. More mist flow per volume of air will yield increasingly lower temperature and higher absolute humidity along the constant enthalpy line up to the limit of saturated air at the wet bulb temperate and 100% relative humidity. Plots of lines of constant Effective Temperature (ET) on the psychometric chart tend to have a more shallow slope than lines of constant enthalpy (ASHRAE, 2013). Although some may suspect that the increase of humidity could outweigh the temperature reduction in terms of thermal comfort, a constant enthalpy cooling process will yield lower and lower values of ET as the cooling effect increases. That is, evaporative cooling will tend to yield improved thermal comfort as the temperature decreases, even though the humidity level increases.

The reduction in air temperature is a function of the amount of evaporated water mist, m_{mist}, and the amount of air with which it interacts, m_{air}. The cooling is a balance between the latent heat of evaporation of the mist and the sensible heat of the air, as in Eq(1).

$$\boldsymbol{m_{mist}L = m_{air}C_P\Delta T} \quad (1)$$

where L is the latent heat of evaporation of water, C_P is the specific heat of air and ΔT is the average temperature drop of the air.

In practice, fine mists will be deployed to evaporate completely, thus m_{mist} is known. However, the amount of air with which it interacts cannot easily be evaluated, making simple theoretical prediction of temperature drops difficult. In the case of a misting fan, one may assume the "best case" of average temperature drop in the misted air is assuming only the amount of blown air, m_{ba} from the fan interacts with the mist.

$$\Delta T = \frac{m_{mist} L}{m_{ba} C_P} \quad (2)$$

with the actual temperature drop varying spatially in proportion to the amount of air interacting with the mist droplets. As surrounding air is entrained into the blown air, the temperature drop will proportionately decrease.

3. Experiments

Test subjects were exposed to the streams of air from 2 identical misting fans. One with the mist function active and one without. They were asked to judge the temperature with their bare hands, and decide which air stream was cooler. This vote and personal data were collected in a series of three experiment trials. The first trial was a proof-of-concept experiment to determine if a misted air stream heated to about the same temperature as the non-misted air stream would be judged as cooler. This was done in summer of 2016. When this proved to be true for most respondents, a second trial was done over a wider range of temperatures, such that the misted air stream was up to 1.7K warmer than the non-misted air. This trial was done indoors in autumn of 2016. A third trial, similar to the second trial, was done outdoors during the summer of 2017.

3.1. Experiment apparatus

As the goal of the experiment is to isolate the effect of any expectation of cooling due to the visual perception of mist or other psychological effects from the actual cooling effect, a mist fan with a relatively small cooling effect was chosen. Here, two commercially available fans of the same model with included ultrasonic mist generators were used. Ultrasound typically creates mist with average droplet diameter of about 10µm. The mist spray rate was measured by weight change of the water supply tank over 3 hours. The blown air volume was measured by attaching a circular duct to the fan outlet, then measuring the wind speed profile inside the duct as per ASHRAE-111, using a hot-wire anemometer (ASHRAE, 2008). The cooling effect of evaporation is determined from the spray rate and the latent heat of evaporation of water, as the left side of Eq.(1). The expected average temperature drop due to mist cooling ΔT_C, can be calculated as the exchange of the latent heat of the evaporating mist for the sensible heat of the blown air, using Eq.(2). These specifications are listed in Table 1. At the fan speed setting used in the experiment, the maximum average temperature drop of the misted air stream is expected to be 0.5K. The fans' spray rate and blown air rate differ by 5% or less. This has no significant effect on the expected temperature drop.

The electric consumption of the fans increases when the misting function is activated. The waste heat of the fan motor and mist spray system will offset some of the cooling effect. This is not included in the temperature drop calculation here. The misting function of these fans yields very little cooling effect, yet provides a visible mist.

The misted air flow was heated by a 10m copper coil of 10mm diameter with circulating hot water at 50-70^{o}C mounted behind one of the fans as a heat exchanger. By adjusting the temperature and flow rate of the water, the blown air temperature could be increased by up to 2K above ambient. In the third experiment trials, the coil was replaced by two 300-Watt electric heaters, yielding a similar heating effect. These were all shielded from the view of the test subjects by a black box.

The temperature of the air streams was measured with thermistor temperature loggers with a rated accuracy of +/- 0.5°C in the first and second experiment trials. Before the experiments, 6 of these loggers were calibrated over a span of 30 minutes. The two that maintained the most uniform reading (within 0.2°C or each other) were used as the sensors for the air stream temperatures. The sensors were placed 50cm from the fans, along the centreline of the fan axis. At a distance of 50cm from the fans, measurement of the horizontal profile, perpendicular to the fan axis, showed that air speed was 2.7m/s along the centreline and dropped to zero at 40cm from the centreline. There was no interaction of the air streams from both fans at the 50cm distance. In all experiments, the mist produced by the fans was seen to completely evaporate within about 25cm of the fan, thus there was little chance the sensors were wetted. In the third trial, T-type thermocouples connected to a data logger were used to measure the air stream temperature. They were calibrated in a similar manner to the thermistors, with the two thermocouples used always reading within 0.2°C of each other during calibration.

Experiment subjects were all volunteers recruited from passers-by. Thus, there may be some selection bias in that people who expect the mist to be unpleasant may have chosen not to participate.

Table 1. Specifications of the misting fans

Specification	Fan A	Fan B
Spray rate	**165g/h**	**171g/h**
Blown air, medium setting	**0.20m^3/s**	**0.21m^3/s**
Power consumption, fan only	**46W**	
Power consumption, fan and mist	**78W**	
Evaporative cooling effect	**112W**	
Expected average temperature drop	**0.5K**	

3.2. Procedure of the first experiment trial

The first experiment trial was a proof-of-concept designed to determine if a misted air stream at about the same temperature as the non-misted "fan only" air stream would be judged as cooler by the test subjects. The experiment was conducted outdoors in Osaka, Japan.

Subjects were told the experiment was a comparison of the cooling effect of fans with or without mist. They were not told about the temperature change. Subjects were recruited from the visitors to the Osaka City University open campus event, August 6-7, 2016. 151 people participated. The average age was 19, with most subjects being high school students and some parents. The weather on each day was sunny and among the hottest days of the year, the nearest meteorological station at Sakai recorded a high temperature of 35.5°C on Aug. 7 and 35.4°C on Aug. 8. The test area was well-shaded by buildings and trees. The misting fan and non-misting fan were switched for the second day.

Subjects were asked to use their hand(s) to feel the air in front of each fan and then answer a simple survey form as to which fan felt cooler, or if both felt the same. The time was also noted. Subjects could take as much time as desired, but all made a judgment within 30 seconds. The temperature of each air stream was later found by matching the recorded time on the subjects' survey form to the recorded temperature data. Temperature data was recorded at 10-second intervals. The temperature readings were not visible to the test subjects.

In this trial, some subjects placed their hands very close to the fan, within the non-evaporated mist cloud. This may have affected their perception due to slight wetting.

3.3. Procedure of the second experiment trial

The first trial showed that subjects perceived the stream of misted air to be cooler than the non-misted air, even though their temperatures were about the same. The procedure of the second trial was largely the same as the first trial. This trial was conducted with a wider range of temperature difference between the misted and fan only air streams to determine to what extent the warmer misted air stream would be perceived as cooler than non-misted air. The misted air was warmed up to 1.7K higher than the fan only air stream. Further, to prevent the possible influence of wetting by touching the mist cloud and increase the uniformity of the subjects' experience, subjects were instructed to place their hands 50cm from the mist fans, though free to move hands anywhere within the air streams at the 50cm distance. Coloured cones were placed with the apex at 50cm from each fan, slightly below the centreline of the air stream, to indicate this boundary. This setup is shown in Figure 1, where the "X" marks indicate the position of temperature sensors. A photo is shown as Figure 2, with sensors indicated by number. Sensor 1 is a backup sensor for the non-misting fan air stream. Sensor 2 is a backup sensor for the misted air-stream, in a location that is not affected by the mist. The mist originates from the disk at the centre of the fan grill. Sensors 3 and 4 are those used to record the temperatures of the non-misted "fan only" and misted air streams, respectively. Sensor 5 recorded the ambient temperature.

The trial was conducted indoors on 4 days in October and early November of 2016. The misting fan and non-misting fan were switched each day. The room temperature ranged from 18-22^{o}C during the experiments. 99 test subjects participated. The average age was 20, consisting solely of university students.

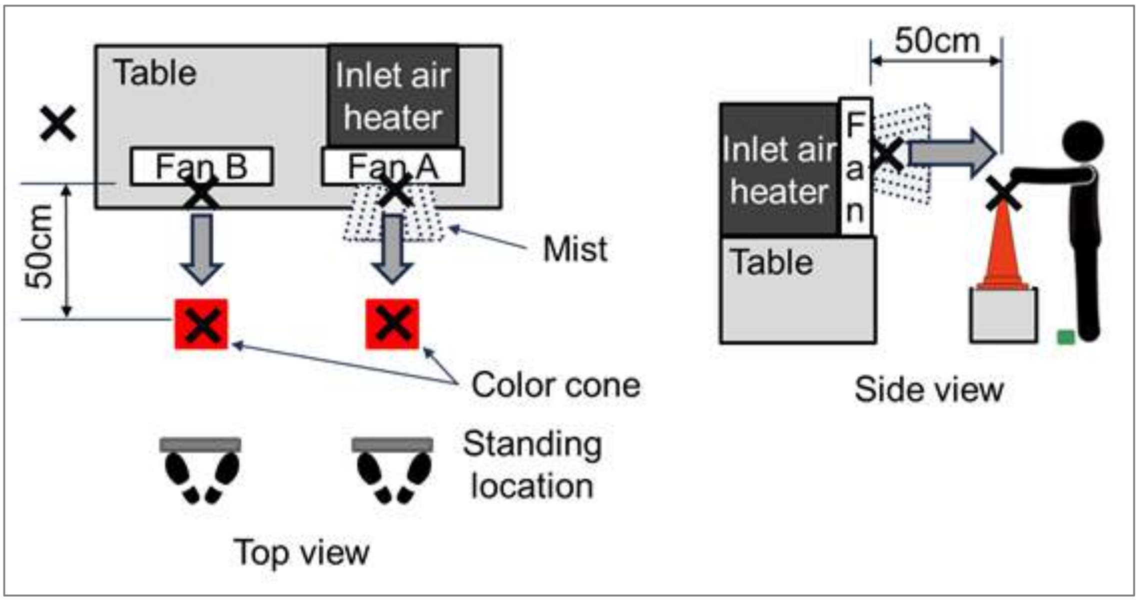


Figure 1. Setup of the misting fan experiment.

Figure 2. Photo of the experiment setup of the second (indoor) experiment trial.

3.4. Procedure of the third experiment trial

As the second trial was done indoors during the autumn, when temperatures were much lower than in typical use of misting fans, a third trial was conducted in the summer of 2017 to confirm whether the results were replicable in hot summer conditions. This trial was also conducted during the open campus event. The colour cones were again used to indicate the 50cm distance where subjects were instructed to place their hands. For this trial, T-type thermocouples were used to measure the temperature in the air streams. The heating of the misted air stream was done with electric heaters.

142 people participated. However, the temperatures were not logged for the more than half of the subjects due to operator error. Temperature data was only available for 53 of the test subjects. Only these data were used for this trial. The weather on each day was sunny and among the hottest days of the year, the nearest meteorological station at Sakai recorded a high temperature of 36.4^{o}C on Aug. 5 and 35.9^{o}C on Aug. 6.

4. Results

The temperature difference between the misted air stream and the non-misted “fan only” air stream was taken from the recorded data of the sensors 50cm from each fan and compared to the survey responses of the subjects. There are 3 possible responses to the survey; the misted air stream felt cooler, “mist”, the non-misted air stream felt cooler, “fan only” or no difference could be determined, “same”. As the 3 trials were conducted under different conditions, the results of each trial are presented separately here.

The first trial was over a relatively narrow range of temperature difference, ΔT. Positive values indicate that the misting fan air stream was warmer. Figure 3 shows the percentage of responses for “mist”, “same” and “fan only” as to which air stream felt cooler. The number of responses in each bin is noted above each bar in the graph as “n”.

Here, the temperature difference ranged from -0.3K (the mist was actually cooler) to +0.5K (the mist was 0.5K warmer than the “fan only” case). The responses are nearly uniform at about 80% choosing the misted fan at all temperatures. No subjects chose the “fan only” case when the mist case was actually cooler. These results showed that the warmed mist air stream could be perceived as cooler. The extent to which this would hold true was unknown, thus the second and third trials extended the temperature difference up to about +2K. Further, some subjects placed their hands within the mist, which may have caused some wetting, which would yield contact evaporation cooling in addition to any cooling effect of the air stream. Thus, a boundary was set at 50cm in the following trials, such that no wetting was possible.

The second trial extended the temperature difference up to +1.7K. The responses are shown in Figure 4. The choice of “mist” as the cooler air stream is present until the 0.5K>ΔT>0.7K bin. There was a single outlier “mist” response at the 1.7K level. There were no “mist” responses at the lowest level, even though the misted air stream actually was cooler than the “fan only” stream. However, there were only 4 responses in this bin. At moderate levels of warming up to +0.5K, about half the responses were for “mist”. Due to some variation of the heating system control, fewer responses were obtained at the higher temperature differences. There seems to be a transition in perception at about the +0.5K to +0.7K level.

The third trial focused around the likely transition point, with temperature differences from +0.1K to +1.1K. The responses are shown in Figure 5. The votes for “mist” show a steady trend lower as the temperature difference increases, with the exception of the final bin. However, there were only 5 responses in that bin. “Fan only” responses were about 15% from +0.1K through +0.7K, then increased to 45% above the +0.7K level.

Although the three experiment conditions differ, a compilation of all 303 responses is given in Figure 6. Over 50% of responses are for “mist” up to the +0.7K difference, then the proportion drops sharply. The choice of “fan only” reaches 50% or more for most of the cases over +0.7K. However, the number of data points above +0.9K is a relatively small portion of the total.

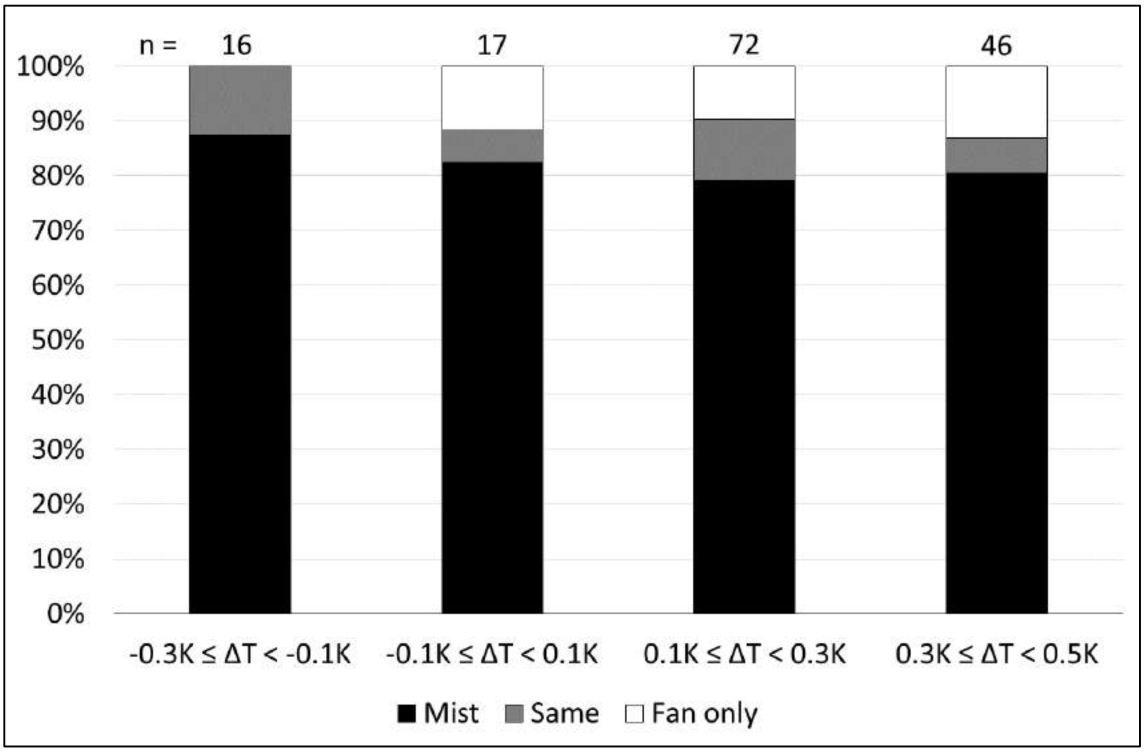


Figure 3. Proportion of responses on which air stream felt cooler. Responses from first experiment trial.

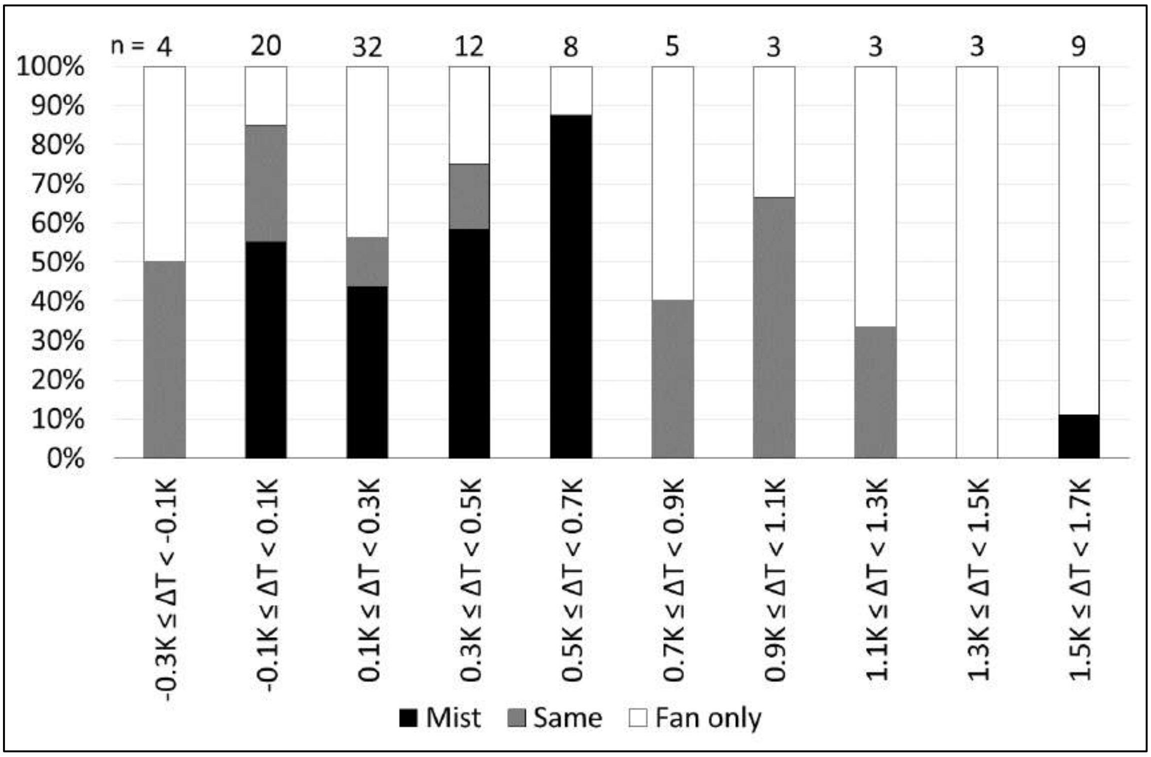


Figure 4. Proportion of responses on which air stream felt cooler. Responses from second experiment trial.

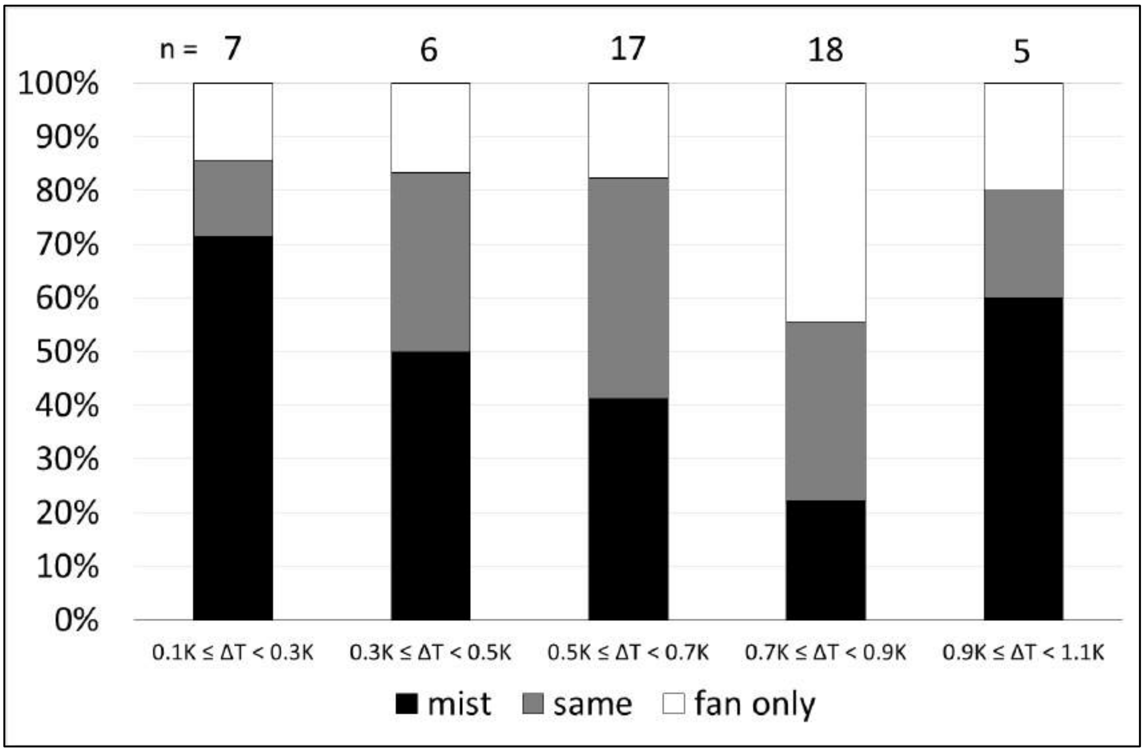


Figure 5. Proportion of responses on which air stream felt cooler. Responses from third experiment trial.

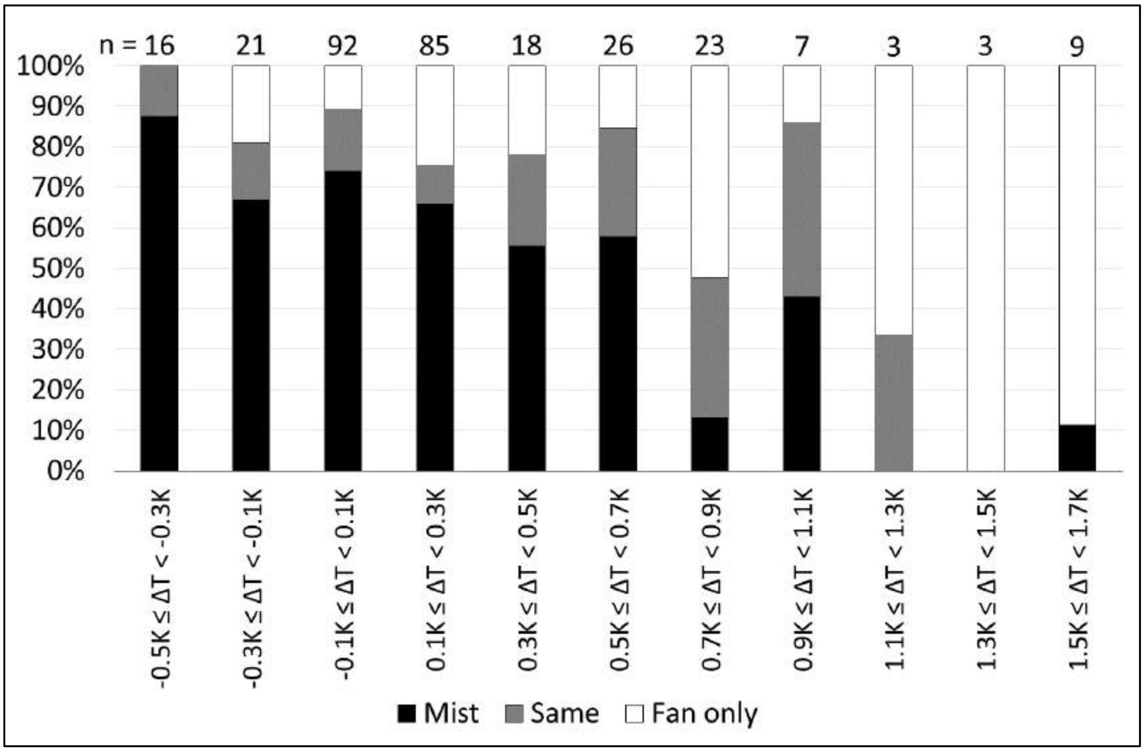


Figure 6. Proportion of responses on which air stream felt cooler. Sum of responses from all 3 experiment trials.

5. Discussion

The test participants showed a tendency to perceive a misted air stream as cooler than a non-misted air stream even when the misted air was warmer. All three experiment trials indicate that this is common up to about a +0.5K difference. The wider temperature range of the second and third trials showed a transition between +0.5 and +0.7K to not choose the warmed mist stream as cooler. The trend was present both in hot summer and relatively cool autumn conditions. Thus seasonal acclimation is likely not an influence. In the first experiment trials, some people put their hands in the mist, which may have resulted in a trend to a cooler perception because of slight wetting or more concentrated mist. Thus, the experienced temperature actually may have been cooler, despite the readings of the dry thermometer at 50cm distance.

Switching the fans on alternate days and calibrating the sensors with each other reduce the likelihood that there was a systematic error in the experiments. Experimenters were careful to never mention the true intent of the experiment, explaining it as a simple comparison of misting fans against fans without mist.

The sudden change in thermal conditions (increased air speed and slight change in temperature) and short span of the participants' experience mean that thermal transients must have some influence on the perception of coolness. This is a factor in all mist cooling comfort surveys. However, when the two air stream temperatures were identical, the subjects would be expected to evaluate the misted air and non-misted air as feeling the same. Yet, there is a strong tend to evaluate the mist as cooler, which extends until the mist was actually 0.5K-0.7K warmer. The transient cooling effect of sudden exposure to blown air would be similar from each fan, but when the misted air stream was warmer, it would add a warming component to the transient. A perception of more cooling even when the thermal transient towards coolness has been reduced or even reversed is unusual.

There may have been other sources of bias, such as the psychology of the subjects. Although the goal is to determine the extent of a trend to vote that mist is cooler, this perception may not be solely due to an expectation that mist is cool. Subjects may have been motivated to be "good subjects" who seek overt or implicit cues to validate the experiment hypothesis. Care was taken to avoid overt cues, by not telling participants the true experiment hypothesis. Yet the test question itself, "Which feels cooler?" may prompt the participant to make a choice, even though they were explicitly given the neutral option to vote for both cases as the same. Further, the setting of experimenters conducting an experiment outdoors on hot summer days for long hours while showing clear signs of thermal stress such as sweating may have biased participants toward sympathy for the experimenters' effort. Some participants may have deduced (correctly) that the intent of the experiment was to show that mist feels cooler, and cooperated by giving the "desired" result, voting for mist as feeling cooler. That is, for some subjects the expectation of coolness from mist might have been less of an influence than the expectation that the experimenters want or even "deserve" a reply in favour of the mist as being cooler.

The indoor experiment participants in autumn were all university students in the college in which research on mist cooling has been conducted for several years. Thus, rumours and "campus scuttlebutt" may have influenced the trend to vote as "good subjects" in favour of mist as cooler. On the other hand, the summer experiments were entirely visitors who had not been to the university before and likely had heard no rumours of this type of experiment, yet the results of the summer and autumn experiments were nearly the same. Thus, rumour may not have been a significant factor.

In the experiments detailed here, we have asked the subjects to compare a fan with the special feature of mist to a fan with no special feature. The "desired" result might be easily inferred by the participants that the special device should be chosen. Future experiments will take different approaches to confound subjects' expectations and the good subject effect. Openly placing heater units behind both fans, and telling the participants that the temperature is being controlled, such that it is *possible* that the mist may actually be warmer, could yield a different result. It may even be useful to falsely claim that the "fan only" case has some sort of special function (a positive ion generator or the like) to confound the good subject effect by making both fans "special" and the "desired" result less obvious. Subjects should also be asked if they have experienced mist cooling before, or heard news of mist cooling, which may affect their expectations.

There may be other influences than the visual perception of mist, such as a possible difference in the smell of misted air. However, such an evaluation is well beyond the scope of this experiment.

Work on the research continues with a more thorough statistical analysis of the data, toward the development of a logistic regression of the data to predict this effect. Further experiments are planned to increase the amount of data, especially in the higher range of temperature difference (the misted air stream warmed well above the non-misted stream).

6. Conclusions

The results indicate that there is some bias to perceive mist as cooler than it actually is. When a misted stream of air is secretly heated, subjects will tend to claim it is cooler than a stream of non-misted air, even though the misted air is slightly warmer. This may be due to expectation, but may also be confounded by the "good test subject" effect or other biases. The effect equates to about 0.5-0.7K difference in perceived temperature. Touching the mist is not necessary to yield this effect. This could account for some of the difference between thermal comfort votes in mist and the PMV calculation for misted, blown air. This 0.5-0.7K difference is much smaller than the actual temperature drop of about 2-3K in typical misting installations. Thus, the improved comfort votes in tests of mist likely would not be explained as being entirely the result of expectation and "good subject" effects. Alliesthesia and thermal transient effects are still likely a major factor to be explored in future experiments.

If expectation of cooling yielding stronger perception of cooling is a valid factor, deployment of mist cooling systems could exploit this by ensuring that the mist spray is visible to the persons being cooled. It may be possible that visual cues and experiment subject effects for other types of cooling systems may yield cooler thermal comfort votes than can be explained by the objectively measured thermal conditions.

7. References

ASHRAE, 2013. ASHRAE Handbook - Fundamentals – Chapter 9, Thermal Comfort. Atlanta: ASHRAE.

ASHRAE, 2008. ASHRAE Standard 111-2008 – Measurement, Testing, Adjusting, and Balancing of Building HVAC Systems. Atlanta: ASHRAE.

de Dear, R., Ring, J., Fanger, P., 1993. Thermal Sensations Resulting From Sudden Ambient Temperature Changes. *Indoor Air*, 3, pp 181–192.

Farnham C., Emura K., Mizuno T., 2015. Evaluation of cooling effects: outdoor water mist fan. *Building Research & Information*, 43(3), pp 334-345.

Ronsow, R., Rosenthal R., 1997. *People studying people: artifacts and ethics in behavioural research*. New York: W.H. Freeman.

Uchiyama S., Suzuki K., Tsujimoto S., Koizumi H., 2008. An Experiment in Reducing Temperatures at a Rail Platform. *Japan Society of Plumbing Engineers*, 25(2), pp. 8-11.

Wong, N.H., & Chong, A., 2010. Performance evaluation of misting fans in hot and humid climate. *Building and Environment*, 45, pp 2666-2678.

Yamada H., Okumiya M., Tsujimoto M., Harada M., 2006. Study on Cooling Effect with Water Mist Sprayer. *Summaries of Techincal Papers of the Architectural Institute of Japan Annual Conference*., Kanto, Japan. 7 – 9 September 2006. Tokyo: Architectural Institute of Japan.

Contributions of authors

Craig Farnham, Yuki Okazaki, Miki Kubota, Md Alam Ashraful and Jihui Yuan participated in the experiments with human subjects and tabulating data. Craig Farnham, Yuki Okazaki and Miki Kubota contributed to analysing the data. Craig Farnham and Kazuo Emura evaluated the data in terms of thermal comfort. Craig Farnham wrote this paper, with guidance from Kazuo Emura and Jihui Yuan.

Study on Thermal Indices under Mist Spray Condition through Thermal Sensation and Comfort

Wonseok Oh[1], Ryozo Ooka[2], Junta Nakano[3], Hideki Kikumoto[2], Osamu Ogawa[4]

[1] Graduate School of Engineering, Department of Architecture, The University of Tokyo, Japan, os-ws@iis.u-tokyo.ac.jp
[2] Institute of Industrial Science, The University of Tokyo, Japan
[3] Department of Architecture, Tokai University, Japan
[4] Appliances company, Panasonic corporation, Japan

Abstract: Recently, a cooling system using water evaporation has been widely utilized as an alternative for relieving human thermal stress. The mist spray system is known to be able to lower the air temperature by 1–3 °C in the outdoor environment and increase the thermal sensation. However, the existing mist spray system tends to raise the humidity too high around the human or fail to deliver cooled air properly according to the wind effect. To overcome the problems of the conventional systems, a mist spray with an air-blowing system was proposed. As a result, this mist spray system led to an increase in convection and evaporation effects. In addition, the effectiveness of the system was confirmed by the field experiment. The survey by subjects and the measurement of environmental factors were performed simultaneously in the summer. The surveys were conducted using a seven-point modified thermal sensation vote (mTSV) scale from very cold (-3) to very hot (+3) and the comfort sensation vote (CSV) scale from very uncomfortable (-3) to very comfortable (+3). The results of the survey showed that the mean mTSV value dropped from 2.3 to 0.2, decreasing the degree of feeling hot, and the mean CSV value increased from -1.3 to 1.4, improving the comfort feeling. To confirm the thermal effectiveness of the mist spray system, environmental factors were measured in two different locations where it was and was not influenced by the mist spray, respectively. The factors were air temperature, humidity, wind speed, globe temperature, and solar radiation. Since the inside of the mist is wetted by the influence of the water droplet and cannot be measured with a conventional sensor, a cyclone type of measurement for the dry bulb temperature and density of water vapor were used. To predict the human's thermal state in an outdoor environment and the mist spraying condition, the feasibility of Gagge's two-node model was verified with the field experiment. The results showed that the gap of in the mean skin temperature between the predicted model and field experiment was 0.2–0.3 °C. In addition, this study proposes an environmental index that can predict the mTSV in an outdoor environment and the mist spray condition by a two-node model.

Keywords: Mist spray; Outdoor environment; Thermal sensation; Thermal comfort; Thermal index

1. Introduction

A human's thermal sensation and comfort are greatly influenced by environmental factors such as temperature, radiation, humidity, and airflow around its body. As an endotherm, a human has a thermoregulation system through physiological responses such as sweating, blood flow regulation, and shivering in response to a thermal environment. In practice, the indoor environment is controlled by cooling and heating to improve a human's thermal comfort such that its physiological response does not actively appear much. On the other hands, physiological thermoregulatory responses often occur in hot and cold external environments where environmental conditions cannot be controlled intentionally, and causes thermal discomfort. As a method of understanding the effect of the thermal environment on the human body, further research has been carried out by the physics and physiological approach. In addition, various environmental indices have been developed to evaluate the thermal environment and predict thermal sensation (Havenith & Fiala 2016). However, the verification on whether these environmental indices can be applied in the outdoor environment is lacking. Meanwhile, the mist spray system has been increasingly used as a method to solve heat stress in the outdoor environment (Huang et al. 2017; Montazeri et al. 2017). The mist spray system can lower the temperature by using the latent heat of evaporation of water droplets to control the environment. Although it has been known that thermal stress is reduced while comfort is improved by using the evaporation of water vapor, none have examined the effect considering the environmental indices. Therefore, in this study, we examine whether the representative environmental indices such as the SET * (Gagge & Nishi 2011; Gagge et al. 1972), PET (Höppe 1999), and WBGT are effective in predicting thermal sensation and comfort in the outdoor environment, especially in areas where the mist spray system was installed. If a statistically significant correlation does not exist between the environmental index and a human's thermal sensation, it cannot be regarded as an appropriate evaluation index. To reflect the thermal sensation of a human, it is necessary to consider the heat exchange between the environment and the human body and the physiological response of humans. In addition, the most significant difference between the indoor and outdoor environments is the effect of solar radiation. Recently, environmental indices such as ETU (Nagano & Horikoshi 2011), UTCI (Jendritzky et al. 2012), and OUT–SET* (Pickup & de Dear 2000) have been proposed to consider the effects of uneven radiation environment on the human body. However, in an actual outdoor environment, sufficient comparison with the human physiological index has not been performed.

Gagge's two-node model considers a human's physiological regulatory response in the heat exchange between the human body and the surrounding. Using this model, the average skin temperature and the core temperature of the human body in the outdoor environment can be predicted. Further, the feasibility of the prediction model can be verified by comparing with the measured data. In this study, the mean radiation temperature was predicted through the actual measurement of the radiation in an outdoor environment. In addition, we examined whether this model can be applied in the outdoor environment where the mist spray system is operating, by comparing the experimental results and the two-node model results. Further, this study proposes an environmental index that can be utilized in an outdoor environment and the mist spray environment by analyzing the correlation with thermal sensation.

The main contribution of this paper is summarized as follows:

1. The effect of the mist spray system was verified by confirming the mTSV and CSV.
2. The correlation between the environmental index and human thermal sensation in an outdoor mist environment was demonstrated.
3. The prediction and verification of the thermal state of the human body in an outdoor environment through a two-node model were performed.

2. Methodology

To overcome the disadvantages of the existing mist spray system, a new mechanism is being developed using mist blowing with a forward-curved centrifugal fan, which enables the cooled airflow to transmit effectively to the periphery of the human body. This air blowing system installed inside of the mist facility, which can deliver the outdoor air to mist nozzles with high airspeed. The cooled airflow by sprayed water, transmit effectively to the periphery of the human body. This study was carried out in the following order. First experiment was conducted to confirm the effect of mist in the summer. In this experiment, questionnaires were collected twice, i.e., before and after the subject entered the mist. Besides, we examined whether the existing environmental indices can also be applied to outdoor and mist-spraying environments. By confirming the SET *, PET, and WBGT using measured environmental factors, the correlation between the existing environmental index and the reported human thermal sensation was confirmed. As a result, the existing environmental index was examined to determine whether it is effective in predicting the human thermal sensation in the outdoor and mist-spraying environments.

Secondly, an additional experiment was conducted to verify the model that can predict the thermal sensation even more accurately. In this case, the measurement equipment was added considering factors that had been impossible to measure due to mist spraying. Meanwhile, a human's thermal senses are closely related to its core and skin temperature. Thus, if the thermal condition of the human body under the outdoor environment and the mist spraying condition are known, the thermal sensation can be easily predicted. In this study, the prediction of the thermal state of the human body using Gagge's two-node model considering the physiological response of the human body was verified and its applicability was confirmed.

In the first experiment conducted in Shinbashi in 2016, the questionnaire was conducted for the general public. In the second experiment performed in Fujisawa in 2017, a more detailed analysis was carried out through the additional equipment, and survey was conducted on the volunteers, as well as their skin temperature measurement simultaneously, and infrared photographs were obtained. Both experiments were conducted on Japanese subjects. The subjective scales are shown in Table 1. The thermal sensation vote (TSV) of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) scale is commonly used to evaluate the human thermal sensation but the words “warm” or “cool” imply comfort in Japanese; therefore, the mTSV (Horikoshi et al. 1974) is adequate for the thermal sensation of the Japanese people (Takasu et al. 2017; Rijal et al. 2017). A comfortable feeling was reported by using a seven-point scale as shown in the table. Further, questions were added regarding the feeling of acceptability, wet areas, sense of mist, and airflow. A questionnaire survey was conducted twice, i.e., before and after the mist was sprayed, to determine the effect of this system on the outdoor environment in the summer.

Table 1. Seven-point scale of modified thermal sensation vote and comfortable sensation vote for the subject experiment

Scale	TSV	mTSV	CSV
3	Hot	Very hot	Very comfortable
2	Warm	Hot	Comfortable
1	Slightly warm	Slightly hot	Slightly comfortable
0	Neutral	Neutral	Neutral
-1	Slightly cool	Slightly cold	Slightly uncomfortable
-2	Cool	Cold	Uncomfortable
-3	Cold	Very cold	Very uncomfortable

3. The effect of mist spray

To verify the effectiveness of the newly developed mist spray system, its test system was installed in the Shinbashi station square in Tokyo. This system blocks the solar radiation to a certain extent and the mist is sprayed in the range of 360° to evaporate and cool the air, and the cooled air toward a vicinity of the human body through by an air blowing mechanism. A detailed overview of this mist system is described in Figure 1. Experiments were conducted on August 4–12 to consider the hot and humid environment during summer. The survey was conducted twice, i.e., before and after the mist was sprayed, with more than 1110 participants, as shown in Table 2. A total of 342 women and 768 men participated freely, with the 30–50 age range showing the highest level of participation. The questionnaire was recorded automatically on a tablet PC to confirm the time that the subjects have spent in the mist system. When a subject's retention time is very short, i.e., a few seconds, the data was discarded as it was not suitable for confirming the proper effect of the mist system. The average recorded exposure time on mist spray system of all participants was about 1 minute. The environmental indices were checked through the measured environmental factors and compared with the reported thermal sensation of the participants.

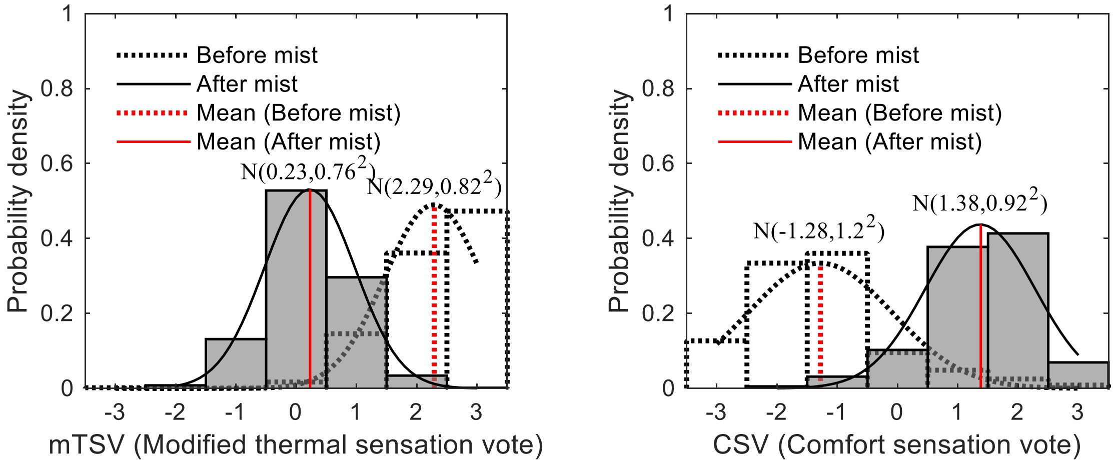
Table 2. Field experiment of the mist spray system (Shinbashi, Tokyo)

Area	Subjects	Number of votes		Period
		Before mist	After mist	
Shinbashi, Tokyo	> 1110	> 1110	> 1110	4–12 Aug., 2016

Figure 1. Mist spray with air-blowing system installed in Shinbashi, Tokyo and its concept (4–12 Aug., 2016)

3.1. Results of mTSV and CSV

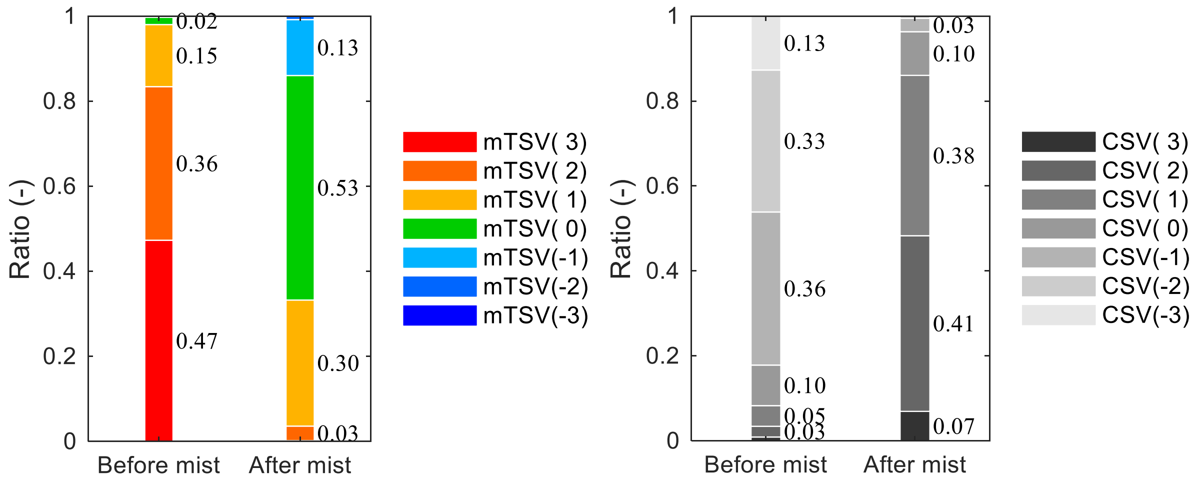
The results of the mist spray system survey are as follows: The mTSV reported by the subject before the mist was sprayed was 2.29, which means that they felt a "hot" to a "very hot" sensation. The mTSV after the influence of the mist spray was reported as a value close to neutral with an average of 0.23. These results confirm that the newly developed mist spray system can alleviate the heat stress in the hot summer outdoor environment. With regard to the CSV index, the range of "slightly uncomfortable" and "uncomfortable" was shown as -1.28 on average because of the hot environment. After the mist spray, the CSV showed a range of "slightly comfortable" and "comfortable", corresponding to 1.38, and the comfortability was improved (see Figure 2).



(a) mTSV (b) CSV

Figure 2. Probability density function N(μ, σ²) of sensation vote results (mTSV and CSV) according to the difference between before mist and after mist environment of outdoor hot season.

The results of the ratio of mTSV (3), mTSV (2), and mTSV (1) corresponding to the sense of thermal environment was 98%, which means that almost everyone reported that the summer outdoor environment was too hot before the mist was sprayed (see Figure 3). These results showed considerable improvement since a ratio of 33% was shown after the mist was sprayed. The ratio of CSV (-1), CSV (-2), and CSV (-3) to the CSV (4) that stands for the neutral state, was 82% before the mist was sprayed. However, only 3.7% of the participants reported an uncomfortable feeling after the mist was sprayed. The ratio of CSV (1), CSV (2), and CSV (3), which stands for the comfort state was 8.3% before the mist, but was improved since 86% of the subjects showed comfortability due to the influence of the mist.



(a) (b)

Figure 3. mTSV result ratio in case of (a): mTSV, (b): CSV.

3.2. Result of acceptability

In the results of acceptability before and after the mist was sprayed, the “Unacceptable” value dropped sharply from 45% to 7% as shown In Figure 4. The proportion corresponding to

“Acceptable” increased from 55% to 93%. In conclusion, we found that most people can accept the mist in an outdoor environment during the hot summer season.

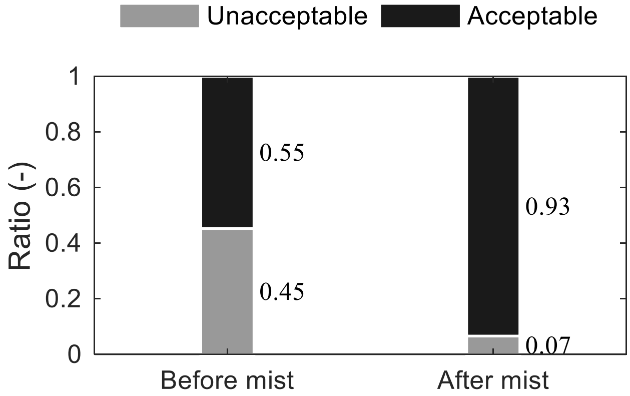


Figure 4. Thermal environmental acceptability of before and after the mist.

3.3. Thermal indices in mist spray environment

In the outdoor environment with mist spray, the existing environmental indices that are expected to predict the human thermal sensation were examined. The environmental indices verified in this study are the SET*, PET, and WBGT. A cumulative density function (CDF) analysis was used to identify the correlations between the existing indices and the reported thermal sensation data by the questionnaire survey. The horizontal axis shows the value of each environmental index, and the vertical axis shows the accumulated ratio of the reported thermal sensation P. In the mTSV case, the value of P is the sum of the values above the surveyed mTSV scale. (i.e., P (1) is the cumulative probability density of the summation of mTSV (1), mTSV (2), and mTSV (3)). In other words, P (1) of the mTSV represents the cumulative rate of all the people who felt above the “slightly hot” level (see Figure 5).

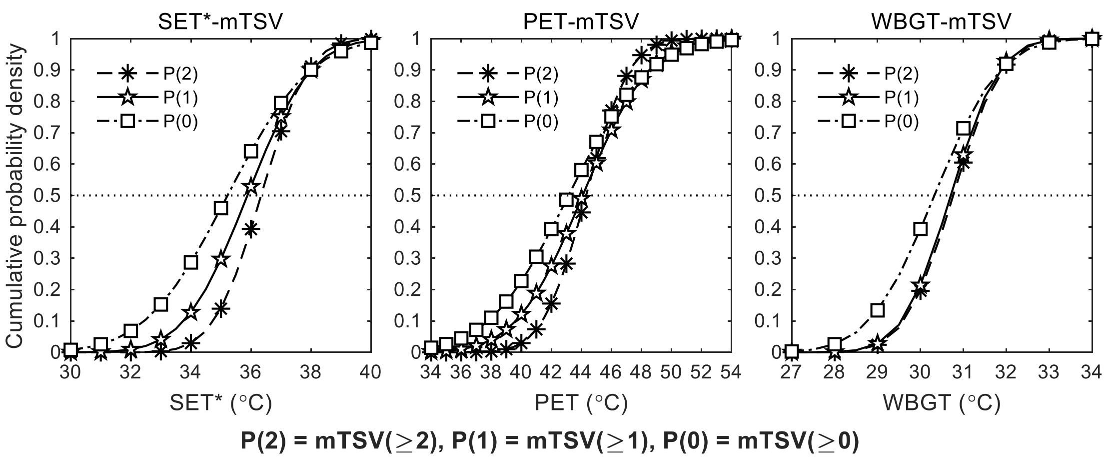


Figure 5. Correlation of mTSV and each thermal index calculated by the measurement results.

In the CSV case, the value of P is the sum of the values less than the reported CSV scale. (i.e., P (0) is the cumulative probability density of the summation of CSV (0), CSV (-1), and CSV (-2)). In other words, the P (0) of CSV represents the cumulative ratio of all the people who felt more discomfort than “neutral” (see Figure 6).

The cumulative ratio of each P and each environmental index showed a positive correlation. Despite the same environmental conditions, all results were shown with different ranges. The PET showed the widest range, while the WBGT showed the narrowest range. In the mTSV case, the distribution of each P was the most recognizable, but the distribution for the PET and WBGT was overlapped or reversed. In conclusion, we confirmed that among the examined environmental indices, only the SET* might be able to predict the mTSV in the outdoor mist spraying environment. Furthermore, in the CSV case, the distribution of each P is overlapped for all environmental indices. Therefore, the existing environmental indices are considered difficult to be utilized for predicting the thermal comfort in the outdoor environment where the mist is sprayed.

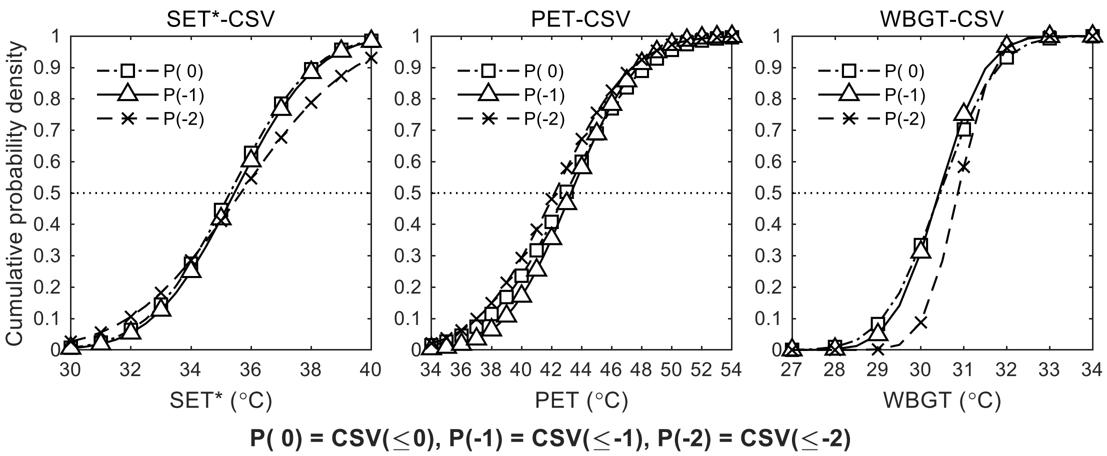


Figure 6. Correlation of CSV and each thermal index calculated by the measurement results.

4. Verification of the two-node model

As mentioned in the earlier section, it was verified that the SET* showed the potential to be used to predict the mTSV. Therefore, an additional experiment has been conducted to verify whether Gagge's two-node model can be applied to the outdoor environment with mist spraying. The experiment was conducted in Fujisawa, Kanagawa in 2017. The mist spray system is basically the same type used in the experiment at Shinbashi in 2016, but differs from spraying mist in a semi-open-type ceiling with the concept of cooling for the bus stop. The experiment was performed for 4 days with 4 participants daily, and the questionnaire was conducted twice, i.e., before and after the mist was sprayed, the same as in the previous experiment as shown in Table 3.

Table 3. Field test of mist spray system (Fujisawa, Kanagawa)

Area	Subjects	Number of votes		Period
		Before mist	After mist	
Fujisawa, Kanagawa	16 (12)[a]	96 (72)[a]	80 (60)[a]	3–4 Aug., 5–6[b] Sep. 2017

Notes: [a]The number of subjects who measured skin temperature. [b]As 6th September was a rainy day, measured data was not used for analysis.

The last day of the experiment was excluded from the analysis because of the temperature drop due to rainfall. In this experiment, the indoor environment of the mist and its outdoor environment were measured and used for the calculation of the environmental index and the two-node model. Simultaneously, the subjects' skin temperature and oral temperature (the reference value of core temperature) were measured and compared with the predicted values. Additionally, the distributions of the whole-body surface temperature between before and after the mist spray was compared using a thermal camera.

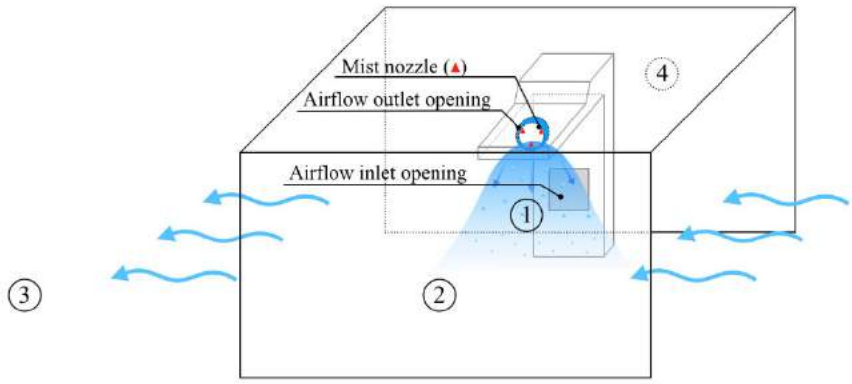
The details of the measurement equipment and the measured points are described in Figure 7 and Table 4, respectively. According to previous studies, the estimation is difficult to perform inside the mist system environment, since the water molecules influence the measurement equipment (Farnham et al. 2011; Farnham et al. 2015). As the inside of the mist cloud is wetted by the influence of the water droplet and cannot be measured with a conventional sensor, a cyclone type of measurement for the dry bulb temperature and density of water vapor in the air by infrared spectroscopy were used. The cyclone type of air temperature measurement was specially devised by Panasonic company to measure a dry air temperature inside the mist spray environment. In this cyclone-type method, the air and the droplet are sucked through the compressor simultaneously, and the droplet is separated to measure only the dry air.

4.1. Measurement of environmental factors

Environmental factors of temperature, radiation, humidity, and wind speed were measured. The details of the measurement equipment are shown in Table 4. The radiation temperature was measured using a globe bulb, a long- and short-wave wavelength meter, and a direct solar irradiation meter. All equipment was installed at a height of 1.1 m, which corresponds to the center of the standing human body. For the measurement of wind speed, an ultrasonic wind gauge and a heat ray anemometer were used. Since the hot wire anemometer cannot be used when it is wetted with water, it is placed in a position where the mist cannot reach, and the measured data is used as reference data. The cyclone-type instrument was installed at heights of 0.2 m, 1.1 m, and 1.7 m, and two sensors were applied at each height to reduce measurement errors. Humidity was measured using an equipment that can measure the water vapor density in the air. In Figure 7, positions 1 and 2 indicate the areas where the sensor is wetted and not wetted by the mist, respectively. Positions 3 and 4 were chosen as they were not shaded by the surrounding buildings outside the mist spray facility.

(c) location 3

(a) Overall view of the mist spray system (b) Inside view (d) location 4



(e) Mist system concept and the location of measurements
(1: Inside of the mist, 2: Near the mist cloud, no wet, 3: Outdoor environment, no shadings, 4: Outdoor environment)

Figure 7. Mist spray system installed in Fujisawa city, Kanagawa, Japan (2 Aug.–6 Sep. 2017)

Table 4. Measurements for the field experiment.

Model	Measuring element	Position
WBGT	Air temperature	1,2,4
	Globe temperature (150 mm)	
	Relative humidity	
Cyclone-type measurement	Air temperature (0.2 m, 1.1 m, 1.7 m)	1
Kanomax climomaster	Airspeed	2
SAT-600	Air velocity (Supersonic anemometer)	1,4
LI-7200 RS	H2O partial pressure	1,4
MR-60	Solar radiation	2,3
STR-22G	Direct solar radiation	3

4.2. Estimation of the MRT in outdoor

Two methods were used to predict the MRT. The first method utilizes the globe bulb and the wind speed (1) (Kuehn et al. 1970), whereas the second method measures the upper and lower two-directional long- and short-wave radiation and the direct solar radiation by tracking the sun (2).

$$T_{mrt} = \sqrt[4]{\left(T_g + 273.15\right)^4 + \frac{h_{cg}}{\varepsilon D^{0.4}}\left(T_g - T_a\right)} - 273.15 \qquad (1)$$

The globe bulb and the long-and short-wave length instruments used for the MRT prediction were installed at two places outside where the influence of mist was not present. Since the direct solar irradiance does not reach the inside of the mist facility, it is installed only on the outer side. According to (Thorsson et al. 2007), the two methods did not differ significant; however, in this study, a clear difference was observed because the 150-mm globe bulb was used, resulting in a slow response rate and a large direct sunlight effect. Therefore, for the prediction of the MRT, the second method was applied.

$$T_{mrt} = \sqrt[4]{\frac{1}{\sigma}\left(f_{eff}\left(\frac{\alpha}{\varepsilon}\cdot\frac{I_{dH}+S\uparrow}{2}+\frac{L\downarrow+L\uparrow}{2}\right)+\frac{\alpha\cdot f_p}{\varepsilon}\cdot I_{dN}\right)} - 273.15 \quad (2)$$

The penetration area of the human body by direct solar radiation can be predicted by the altitude of the sun (3) (Park & Tuller 2011). The altitude of the sun was calculated using the latitude and longitude of Tokyo. In this study, the emissivity of human by the short wave and the absorption rate by the long wave was considered as 0.95 and 0.7, respectively.

$$f_p = 3.01\times10^{-7}\beta^3 - 6.47\times10^{-5}\beta^2 + 8.34\times10^{-4}\beta + 0.298 \quad (3)$$

4.3. Measurement of skin temperature and core temperature

The skin temperature was measured by a simple method to confirm the thermal state of the human body. The measured data were compared with those predicted by the two-node model using environmental factors. Four persons participated daily, but only three persons were measured because of the lack of measuring equipment. The mean skin temperature was calculated by weighting the averages of the seven points of the body segments: head, trunk, forearm, hand, thigh, leg, and foot, as suggested by Hardy and Dubois (4) (Hardy et al. 1938; Choi et al. 1997) Since the core temperature is difficult to measure, the oral temperature was measured and used as the reference data (see Figure 8).

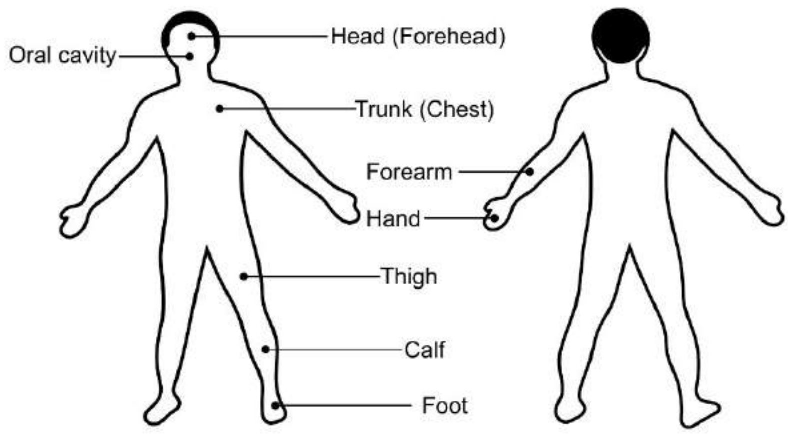


Figure 8. Measured point of the body segments

$$T_{sk} = 0.07\,T_{head} + 0.35\,T_{trunk} + 0.14\,T_{forearm} + 0.05\,T_{hand} + 0.19\,T_{thigh} + 0.13\,T_{calf} + 0.07\,T_{foot} \quad (4)$$

4.4. Two-node model calculation

The predictive models were calculated using 9 participants' skin temperature data. The experimental conditions were set to maintain in the mist for 10 minutes after a subject has walked outdoors for 10 minutes. Subsequently, the feasibility of the two-node model, i.e., whether it can be applied to the outdoor environment and mist spray condition was verified. The environmental factors were used for the 1-minute averages of the measured values, and the varying conditions for 10 minutes of staying in the outdoor environment and 10 minutes of staying in the mist was considered. Since the skin temperature and the experiment time differ for each participant, it was necessary to match the initial conditions to the calculation model such that the mean skin temperature and oral temperature was utilized. The core temperature was examined by substituting the oral temperature. At this time, the subject's metabolic rate and clothing were assumed to be 1.2 met and 0.3 clo, respectively. The model used for the calculation was based on (STANDARD ASHRAE 2013). The neutral body temperature was considered with the proposed formula of (Stolwijk & Hardy 2011).

Table 5. Conditions of the two-node model calculation.

Human	Metabolic rate (met)	1.2
	Clothing (clo)	0.3
	Initial mean skin temperature (°C)	Measured data[a]
	Initial core temperature (°C)	Measured data[b]
	Initial body temperature (°C)	36.21 (0.1 skin + 0.9 core)[c]
	Neutral mean skin temperature (°C)	33.7
	Neutral core temperature (°C)	36.49
	Neutral body temperature (°C)	36.21 (0.1 skin + 0.9 core)
Environment	Air temperature (°C) MRT (°C) Relative humidity (%) Air velocity (m/s)	1-minute intervals for 20 minutes (10 minutes for mist spray condition after 10 minutes for outdoor environment)

Notes: [a]The weighting mean temperature from the measured data. [b]The measured temperature of inside of the oral cavity. [c]Calculated from the initial mean skin temperature and the initial core temperature.

5. Results

The results of the prediction using the two-node model and the field experiment are summarized in this section. As an experiment condition, the subjects were instructed to walk in the outdoor environment for -10–0 minutes, and then move to inside the mist environment and remain there for 0–10 minutes (see Figure 9). We confirmed that the mean skin temperature was lowered when the subjects were staying in the mist. When they were in the mist, their mean skin temperature steadily decreased. As a result, their mean skin temperature dropped by 0.1 ± 0.2 °C in Case 6, which showed the largest difference from the prediction. The overall average results in the decrease of the mean skin temperature by measurement and the prediction model were shown as 0.7 °C and 1.0 °C, respectively. The oral temperature was used as a reference for the core temperature, which often showed fluctuating results. In comparison with the experimental results, the two-node model showed high accuracy in the prediction even in the outdoor environment and mist spray conditions.

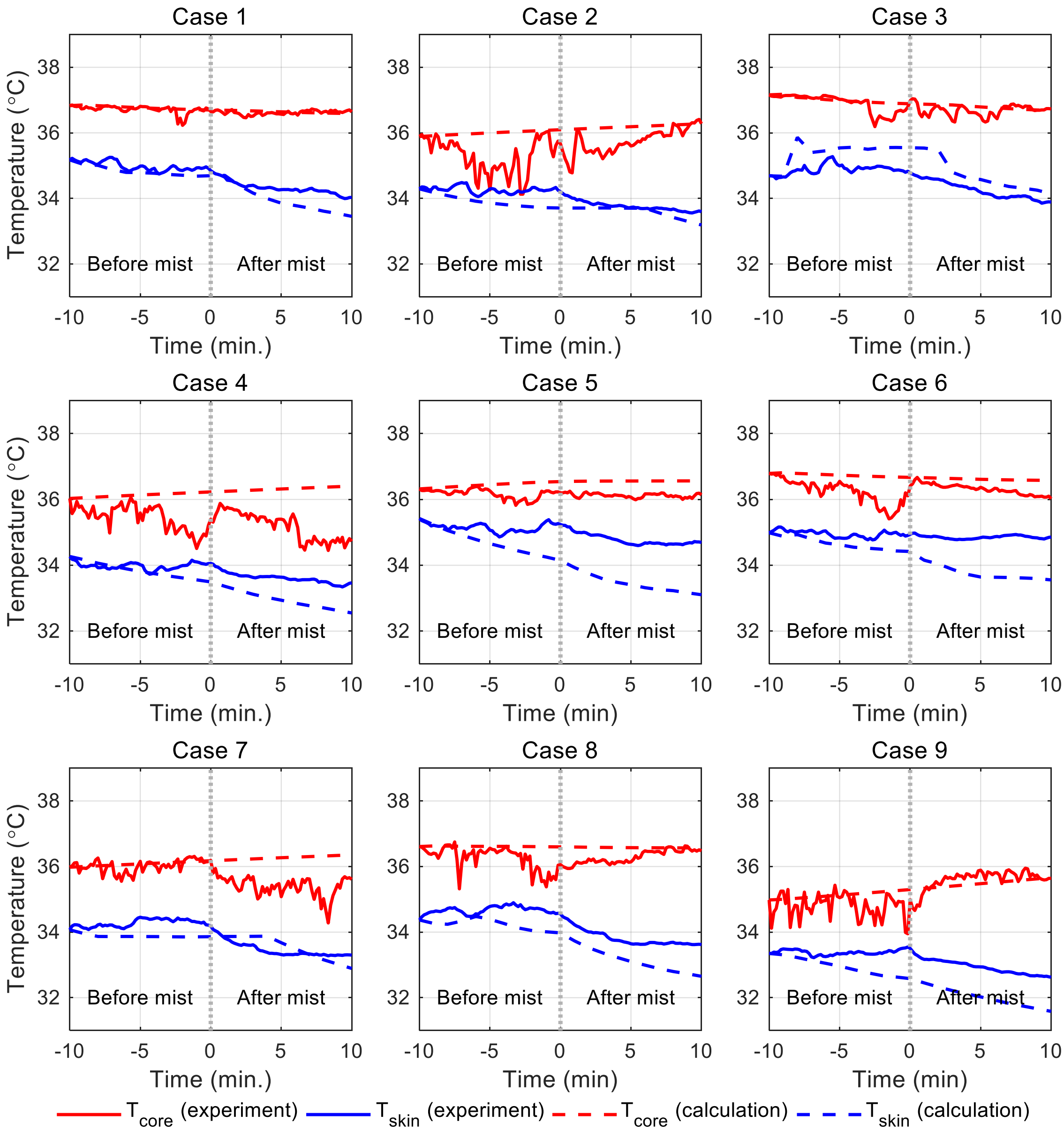
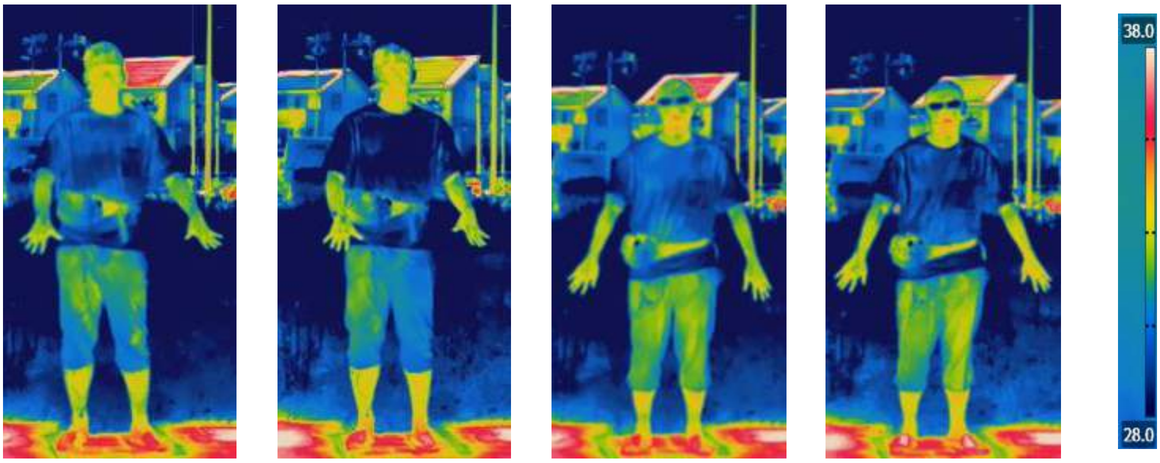


Figure 9. Mean skin temperature and core temperature, outdoor environment conditions for -10–0 minutes, mist spray environment conditions for 0–20 minutes.

Figure 10 shows a few results captured by an infrared camera, before and after the mist. The photographs were taken with the equipment, FLIR T660 with an accuracy of ± 1.0 °C. After the mist, the upper body showed the greatest difference than before the mist, with about 1.0 °C difference. It was also found that the temperature difference between before and after the mist appeared near the head part. Since infrared cameras are not perfectly precise, we only examined the tendency of the cooling effect by the mist.



(a) Before mist (b) After mist (c) Before mist (d) After mist

Figure 10. The results of Infrared camera of before and after the mist, (a)and (b) correspond to Case 7 in Figure 7, (c)and (d) correspond to Case 8 in Figure 7

6. Discussion and conclusions

In this paper, the feasibility study of a two-node model was performed, i.e., whether it can be utilized as a method of predicting a human thermal state in the outdoor environment and mist spray conditions. We proposed a thermal environmental index that can predict a human's thermal sensation in the outdoor and mist spray environments. The conditions of the initial human body were assumed considering the thermal equilibrium state.

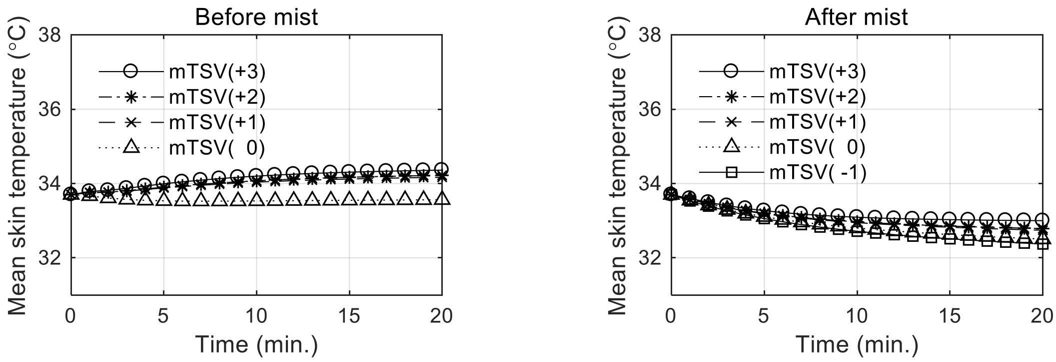
Considering the outdoor environment in the summer, the metabolic rate was set as 1.2 met and the clothing level was set as 0.3 clo. Each result of the mTSV reported before entering the mist and after getting out of the mist was compared. The environmental conditions were set with the constant 10-minute average value of measurement. The detailed conditions of the two-node model for the outdoor and mist spray environment indexes are expressed in Table 6. The rate of heat storage was calculated from the formulation of Fanger's heat balance equation (Fanger 1970) between the human body and the environment as shown in (5).

$$S = (M - W) - E_d - E_s - E_{re} - C_{re} - R - C \quad (5)$$

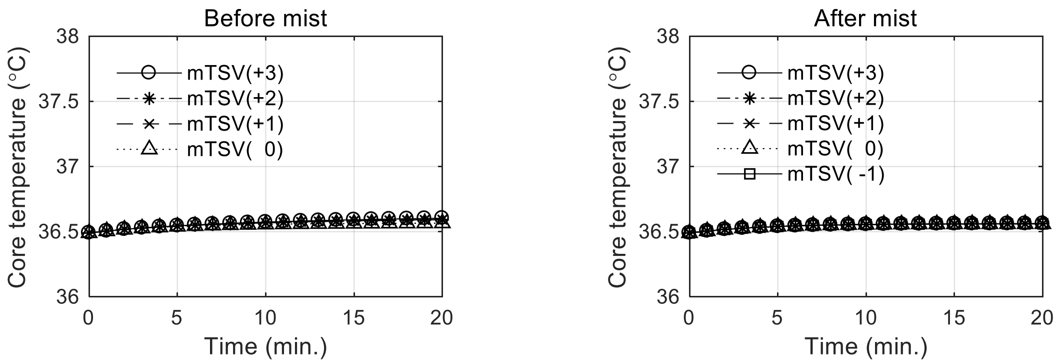
Figure 11 shows the predicted results using the two-node model calculation. The mean skin temperature showed a tendency to increase with the higher mTSV in both before and after mist. The core temperature did not show any significant variations in both conditions. As the mTSV value increased, the physiological response for regulating the body temperature and the wettedness also increased. However, the wettedness was 0.06 after mist, where the thermoregulation by sweat did not occur. In the mist spray condition, the sensible heat loss was increased while the latent heat loss was decreased, since the temperature was lowered and the humidity was increased. The heat storage rate was increased significantly at the early stage of the before mist condition, and decreased gradually by the temperature control response of the human body. After mist was sprayed, the heat storage rate was shown to be less than 0, in which the body has cooled.

Table 6. Conditions of the two-node model calculation for outdoor and mist spray environment indexes

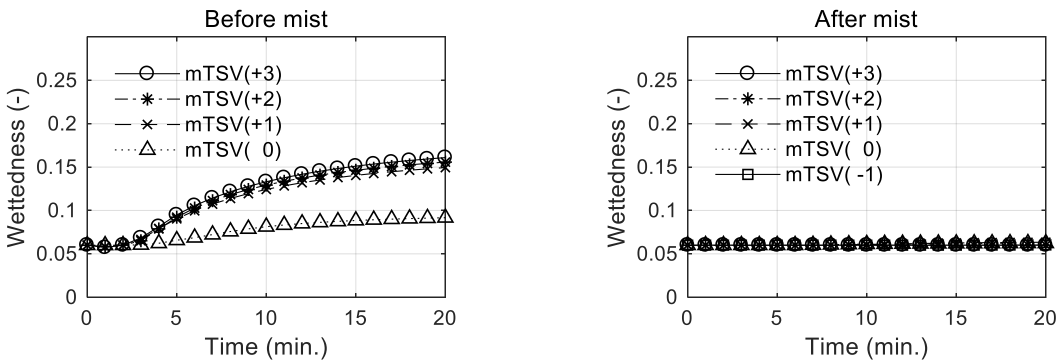
Human	Metabolic rate (met)	1.2
	Clothing (clo)	0.3
	Initial mean skin temperature (°C)	33.7
	Initial core temperature (°C)	36.49
	Initial body temperature (°C)	36.21 (0.1 skin + 0.9 core)
	Neutral mean skin temperature (°C)	33.7
	Neutral core temperature (°C)	36.49
	Neutral body temperature (°C)	36.21 (0.1 skin + 0.9 core)
Environment	Air temperature (°C)	Constant
	MRT (°C)	1. Outdoor (10 min. averaged)
	Relative humidity (%)	2. Mist spray (10 min. averaged)
	Air velocity (m/s)	



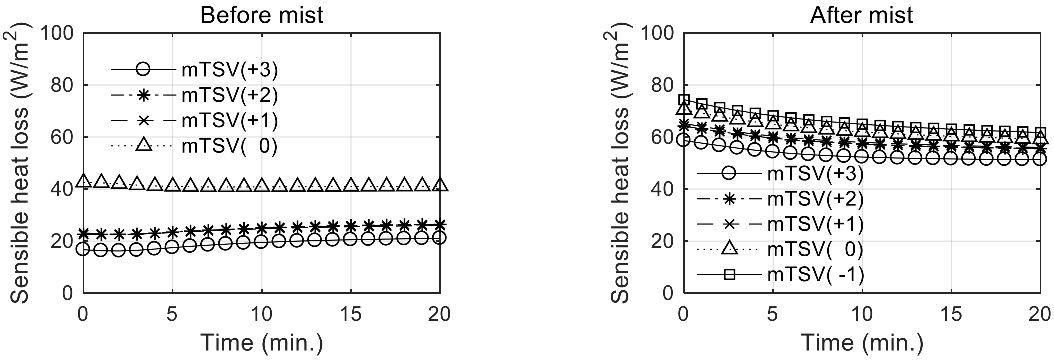
(a) Mean skin temperature



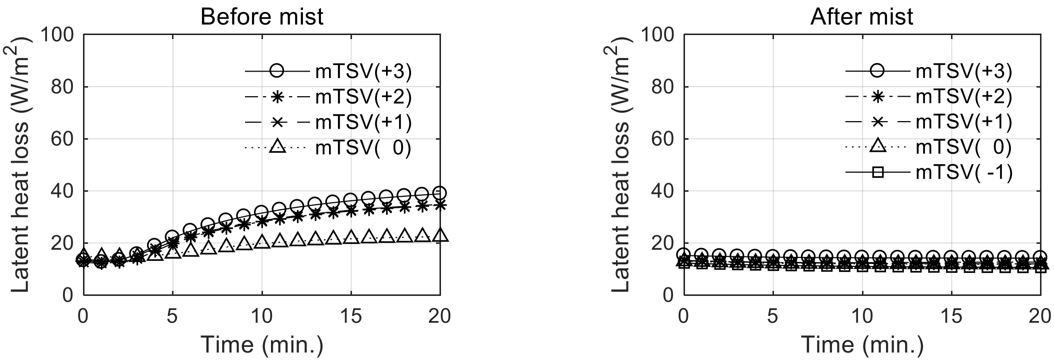
(b) Core temperature



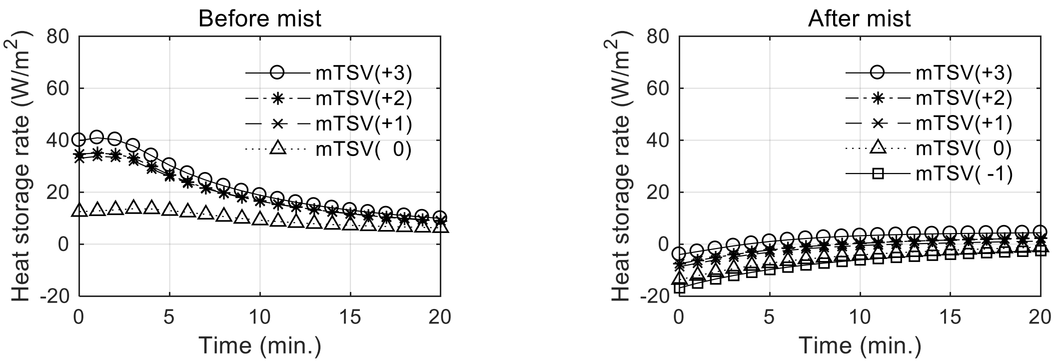
(c) Wettedness



(d) Sensible heat loss



(e) Latent heat loss



(f) The rate of heat storage

Figure 11. Predicted results by two node model calculation.

Fanger suggested the PMV index, which predicts thermal sensation through the correlation between the results of vote and the rate of heat storage. This PMV can be described as in equation (6):

$$PMV = \frac{\delta TSV}{\delta S} \times S = f(x) \times S \tag{6}$$

The SET*, the range of heat storage converges to 0 owing to the physiological responses because the steady state was assumed. Further, it is inappropriate to consider the situation where people are exposed in a hot outdoor environment for 60 minutes. In the experiment, participants were instructed to stay inside the mist for 10 minutes. Therefore, this study suggests using the rate of heat storage results after 10 minutes of exposure to the hot outdoor environment and mist spray conditions to predict the mTSV. Figure 12 and Equation (7) show the results of the correlation between the heat storage rate and the mTSV at 10 minutes before and after mist.

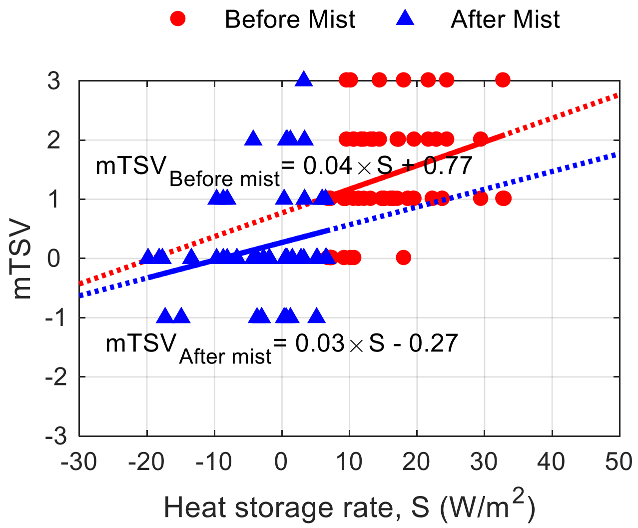


Figure 12. Correlation between the rate of heat storage and mTSV at 10 minutes before and after mist

$$mTSV_{before\ mist} = 0.04 \times S + 0.77$$
$$mTSV_{after\ mist} = 0.03 \times S - 0.27 \quad (7)$$

Before and after the mist, the averaged result of the heat storage rate in the overall cases were shown as 0.93 met (54.1 W/m^2) and 1.23 met (73.1 W/m^2), respectively, as shown in Figure 13. This result indicates that the human body was heated by the environment before mist, and cooled down after mist.

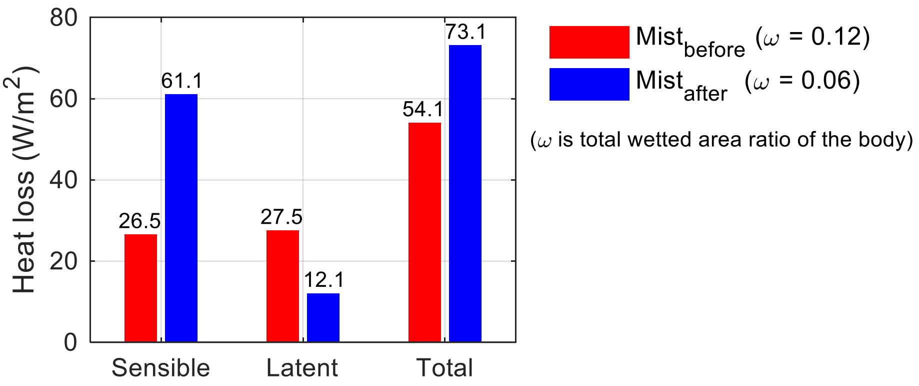


Figure 13. Mean heat loss at 10 minutes before and after mist

Nomenclature

h_{cg}: Mean convective coefficient, 1.10×10^{8} $V^{0.6}$

D: Diameter of globe temperature, 0.15 (m)

T_g: Globe temperature (°C)

T_{mrt}: Mean radiant temperature (°C)

I_{dH}: Direct solar radiation on a horizontal surface ($S\downarrow - I_{dN} \cdot sin\beta$, W m^{-2})

I_{dH}: Direct solar radiation on a normal surface (W m^{-2})

β: Solar altitude (Location: Tokyo)

$S\downarrow$: The downward short-wave radiation (W m^{-2})
$S\uparrow$: The upward short-wave radiation (W m^{-2})
$L\downarrow$: The downward long-wave radiation (W m^{-2})
$L\uparrow$: The upward long-wave radiation (W m^{-2})
σ: Stefan-Boltzmann constant (5.67×10^{-8}, W m^{-2} K^{-4})
f_{eff}: Effective area factor by radiation, 0.87 (-)
f_p: Body's projected area factor by direct solar radiation (-)
α: Absorptivity of the clothed human body by short-wave radiation, 0.7 (-)
ε: Emissivity of the clothed human body by long-wave radiation, 0.95 (-)
M: Metabolic heat production (W m^{-2})
W: Mechanical work accomplished (W m^{-2})
S: The rate of heat storage (W m^{-2})
E_d: Heat loss by water vapor diffusion through skin (W m^{-2})
E_s: Heat loss by evaporation of sweat from skin surface (W m^{-2})
E_{re}: Latent heat loss by respiration (W m^{-2})
C_{re}: Sensible heat loss by respiration (W m^{-2})
R: Radiative heat loss from clothed surface of the body (W m^{-2})
C: Convective heat loss from clothed surface of the body (W m^{-2})

References

Choi, JK et al. 1997 'Evaluation of mean skin temperature formulas by infrared thermography' *International Journal of Biometeorology* 41/2:68–75

Fanger, PO 1970 'Thermal comfort. Analysis and applications in environmental engineering' *… comfort Analysis and applications in environmental …*

Farnham, Craig et al. 2011 'Study of mist-cooling for semi-enclosed spaces in Osaka, Japan' *Procedia Environmental Sciences* 4:228–238

Farnham, Craig; Emura, Kazuo & Mizuno, Takeo 2015 'Evaluation of cooling effects: Outdoor water mist fan' *Building Research and Information* 43/3:334–345

Gagge, AP & Nishi, Y 2011 'Heat exchange between human skin surface and thermal environment' *Comprehensive Physiology*

Gagge, AP; Stolwijk, JAJ & Nishi, Y 1972 'An effective temperature scale based on a simple model of human physiological regulatory response' *ASHRAE Transactions* 77

Hardy, James D; Du Bois, Eugene F & Soderstrom, GF 1938 'The technic of measuring radiation and convection' *The Journal of Nutrition* 15/5:461–475

Havenith, George & Fiala, Dusan 2016 'Thermal indices and thermophysiological modeling for heat stress' *Comprehensive Physiology* 6/1:255–302

Höppe, P 1999 'The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment' *International Journal of Biometeorology* 43:71–75

Horikoshi, Tetsumi; Isoda, N & Kobayashi, Y 1974 'Experimental study on the effect on the human body of the thermal conditions in the wind tunnel in Japanese' in 1974 *The Society of Heating, Air-Conditioning Sanitary Engineers of Japan* 22–30

Huang, Chen et al. 2017 'Solving model of temperature and humidity profiles in spray cooling zone' *Building and Environment* 123:189–199

Jendritzky, Gerd; de Dear, RJ & Havenith, George 2012 'UTCI-Why another thermal index?' *International Journal of Biometeorology* 56/3:421–428

Kuehn, LA; Stubbs, RA & Weaver, RS 1970 'Theory of the globe thermometer' *Journal of Applied Physiology* 29/24:750–757

Montazeri, H et al. 2017 'Simulating the cooling effects of water spray systems in urban landscapes: A computational fluid dynamics study in Rotterdam, The Netherlands' *Landscape and Urban Planning* 159:85–100

Nagano, K & Horikoshi, Tetsumi 2011 'New index indicating the universal and separate effects on human comfort under outdoor and non-uniform thermal conditions' *Energy and Buildings* 43/7:1694–1701

Park, Sookuk & Tuller, Stanton E 2011 'Human body area factors for radiation exchange analysis: Standing and walking postures' *International Journal of Biometeorology* 55/5:695–709

Pickup, J & de Dear, RJ 2000 'An outdoor thermal comfort index-part I - The model and its assumptions' *Biometeorology and Urban Climatology at the Turn of the Millennium. WCASP 50: WMO/TD No.1026* /January:279–283

Rijal, Hom B; Humphreys, Michael A & Nicol, J Fergus 2017 'Towards an adaptive model for thermal comfort in Japanese offices' *Building Research & Information* 45/7:717–729

STANDARD ASHRAE 2013 'Standard 55-2013: Thermal environmental conditions for human occupancy'

Stolwijk, Jan AJ & Hardy, James D 2011 'Control of body temperature' in 2011 *Comprehensive Physiology* Hoboken, NJ, USA: John Wiley & Sons, Inc.: 45–67

Takasu, Marina et al. 2017 'Study on adaptive thermal comfort in Japanese offices under various operation modes' *Building and Environment* 118:273–288

Thorsson, Sofia et al. 2007 'Different methods for estimating the mean radiant temperature in an outdoor urban setting' *International Journal of Climatology* 27/14:1983–1993

Evaluation of Radiant Ceiling Heating Systems for Renovated Buildings based on Thermal Comfort Criteria

M. Reza Safizadeh[1] and Andreas Wagner[1]

[1] Building Science Group, Institute for Building Design and Technology, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
Reza.safi@kit.edu

Abstract: This study aims to evaluate the potential application of low-temperature radiant ceiling heating systems in new and energy-renovated buildings having a low space heating load, based on thermal comfort criteria. Towards the goal, subjective experiments (within-subjects) with 14 participants were performed in an indoor climate test facility. Local and overall thermal sensation and comfort responses in connection to four different scenarios (combinations of ceiling temperatures of 28 and 35°C and distances of 1 and 3 m to the window) were collected using questionnaires. During the experiments, room air temperature, humidity, velocity and globe temperature, as well as skin temperature at eight body-points were measured. Findings of this research prove that the radiant ceiling heating system operating at even low temperatures (28-35 °C) can provide fairly neutral thermal sensation and satisfactory comfort at the majority body-parts, if the building envelope satisfies advanced building energy-efficiency regulations. The overall thermal sensation and comfort closely follow the local votes at the upper-body limbs. Beyond the expectation, the head is perceived as the most comfortable body part, despite it is a sensitive extremity to warm conditions. Furthermore, the results show that unlike the local comfort votes, the local sensation votes are strongly related to the local skin temperatures.

Keywords: Radiant heating systems, Thermal comfort, Experiments, Radiant ceiling heating, Renovated building

1. Introduction

By shifting the attention to low-temperature heating systems such as heat pumps with relatively low operating cost (Palzer *et al.*, 2014), low-temperature radiant heating devices have become progressively attractive. Concerning some important factors in the selection of a heating device such as heating performance, compatibility with low-temperature systems and simplicity of renovation process, ceiling heating systems can be a suitable candidate to satisfy the requirements. However, ceiling heating systems often create asymmetric thermal environments, which may cause local discomfort at some body parts and reduce the thermal acceptability of indoor conditions. Therefore, it is necessary to investigate the influence of the radiant ceiling heating systems on occupants' thermal comfort and their potential applications in new and energy-renovated buildings having a low heating load.

Few studies investigated the effect of heated ceilings on subjective thermal comfort systematically (McNall *et al.*, 1970; Griffiths *et al.*, 1974; Fanger *et al.*, 1980). Fanger (Fanger *et al.*, 1980) performed experiments in a thermally neutral environment with a constant operative temperature. The analysis of subjective votes showed that only one participant (out of 16 participants) felt uncomfortable with an asymmetric temperature of 4K at a height of 60 cm. Griffiths et al. (Griffiths *et al.*, 1974) kept the mean radiant temperature at a constant temperature. In their study, 100% of participants found the condition acceptable even for the ceiling temperature of 45 °C. The results of these studies appeal that the radiant ceiling heating system can provide thermal comfort conditions. However, in these studies, the experimental conditions were controlled at constant operative or radiant temperatures, which may not happen in practical situations where the operative and radiant temperatures are dependent on room surface temperatures.

The main challenge in the evaluation of the radiant ceiling systems is the analysis of the thermal comfort criteria in asymmetric thermal environments created by the ceiling heating system. In contrast to the uniform thermal environments, in asymmetrical environments, we cannot estimate overall thermal sensation and thermal comfort based on equal heat flux at all body parts, equivalent mean skin temperature and thermal environmental properties at one single point in spatial space (Zhang *et al.*, 2006). In asymmetrical environments, the overall thermal sensation and overall thermal comfort depend on the local skin temperatures, the local thermal sensation and comfort perception, and the thermal environmental properties near to each body part. Wyon et al. (Wyon *et al.*, 1989) and Nilsson et al. (Nilsson *et al.*, 2007) presented the concept of "Piste" for asymmetric conditions that relates the local thermal comfort status at 16 body parts to the equivalent homogeneous temperature (EHT). However, these models are limited to specific experimental conditions tested and EHT ranges are not related to the human physiological parameters such as local skin and core temperatures (Huizenga *et al.*, 2006; Zhang *et al.*, 2010). Concerning limitations on the use of existing physiological (heat balance based) thermal comfort models such as Fanger's model (ASHRAE-55, 2017) to describe the comfort criteria in the asymmetrical environment, a subjective experimental study is the first and precise approach to evaluate ceiling heating systems based on the subjective comfort votes

Although few studies about the radiant ceiling heating and comfort conditions are available, the detailed analyses of ceiling heating systems and their influence on the local thermal sensation and comfort in practical situations in energy-renovated residential buildings have not been done. The goal of this study is to investigate the potential application of ceiling heating systems in energy-renovated and new buildings based on the local thermal comfort criteria. Towards the goal, subjective experiments (within-subjects) related to four scenarios were performed in an indoor test facility. These scenarios were developed based on a combination of two radiant ceiling temperatures (28 and 35 ˚C) and distances of 1m and 3m to a window with lower surface temperature. The effect of the radiant heating system on the local thermal sensation and comfort of occupants was investigated using questionnaires and physical measurements of skin temperature and thermal environmental properties. The result section of this paper reports the experimental local thermal sensation and comfort votes and the relation between the local votes and the local skin temperatures in connection to the four scenarios, and section 4 summarizes the results of this work and draws conclusions.

2. Methodology

2.1. Experimental design

The first set of experiments was performed with 14 subjects (18-32 years) including eight females and six males in an indoor climate test facility (discussed in section 2.2) from 31st January to 3rd of March 2017. In this study, the influence of the ceiling temperature and the distance to the window on the subjective local thermal sensation and comfort has been studied in four different scenarios given in Table 1. Two values were set for each variable including 28 °C and 35 °C as the ceiling temperatures, and 1 and 3 meters for the distance to the window with a lower surface temperature (see also Table 4).

Table 1: Experimental scenarios

Scenarios	Ceiling temperature	Distance to the window
Scenario-1	35 °C	3 m
Scenario-2	28 °C	3 m
Scenario-3	28 °C	1 m
Scenario-4	35 °C	1 m

Figure 1 presents the timeline for daily experiments. After arrival, the participants were requested to have a seat in an anteroom for acclimation, introduction of experiments, attachment of sensors and filling the daily background questionnaires. After 30 minutes, the participants were asked to enter the test-room, to be sedentary at the computers (Figure 3.b) and to answer the first short questionnaire. The 2nd short questionnaire (similar to the 1st questionnaire) was popped up on the screen after 15 minutes and the last comprehensive questionnaire was popped up after 60 minutes from entering the room. After finishing the last questionnaire, some thermal images from the participants and the room surfaces were taken. During the experiments, the subjects' skin temperature at eight body positions and the thermal environmental parameters of the room such as air velocity, air temperature, air humidity and globe temperature were measured with the time-resolution of 1 min.

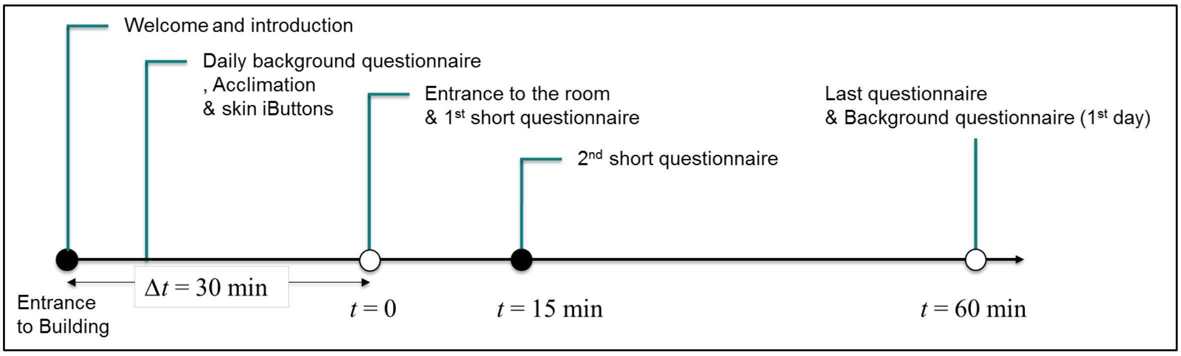


Figure 1: Timeline for daily experiments and questionnaires

The questionnaires were designed to assess the participants' overall and local thermal sensation and comfort. Figure 2 presents exemplarily questions about thermal sensation (ASHRAE 7-point scale), thermal preferences (5-point scale) and thermal comfort (4-point scale). The first and second questionnaires contained few questions about the local thermal sensation perception at 10 body-points. These 10 points were selected based on the EN-ISO 9886 (ISO-9886, 2004) including the top of the head, forehead, right scapula, left upper chest, right upper arm in upper location, left lower arm in upper location, left hand, left calf and right foot. Additionally, a question was asked to realize the perceived temperature asymmetry between the left and right body's limbs including the arms, legs, hands, feet and shoulders. The final comfort questionnaire was relatively long and contained questions about the overall thermal sensation, thermal sensation preference, overall thermal comfort, humidity acceptance and preference, air quality, perceived room air temperature, local thermal sensation (at 10 body-points), local thermal comfort (at 10 body-points) and asymmetric body-temperature.

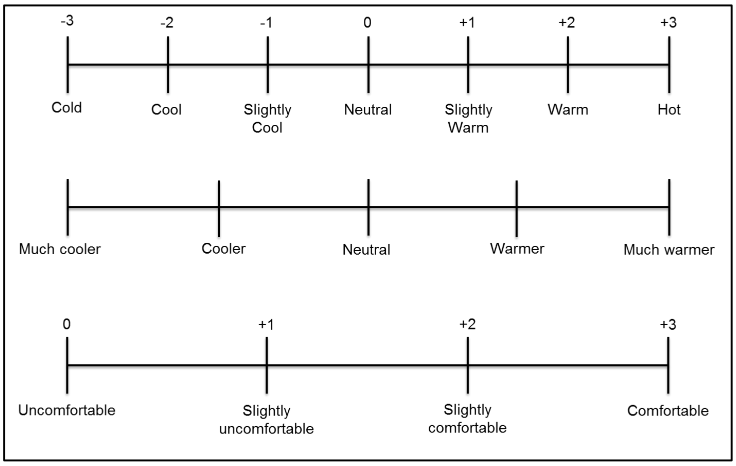


Figure 2: Discrete comfort scales: thermal sensation, thermal preferences, and thermal comfort

2.2. Indoor climate test facility

Experiments took place in an indoor climate test facility (called LOBSTER) located at the Karlsruhe Institute of Technology (KIT). A detailed description of the LOBSTER was reported by A. Wagner et al. (Wagner *et al.*, 2017). The LOBSTER contains two test-rooms (4x6x3 m^3) and a small preparation room for acclimation and preparation of participants. It is equipped with radiant systems in the walls, the ceiling and the floor. The surfaces are cooled and warmed by capillary tubes and additional convectors are air-to-water heat exchangers. In this combination of systems, each surface of the room can operate at different temperatures depending on the experimental conditions. In the recent experiments, only individual surfaces including walls, floor, and ceiling were operating at specific temperatures in order to imitate the surface temperatures of a room with standard building envelope elements in winter. Table 2 shows the surface temperatures that were set in the experiments. The façade was directed to the north in order to minimize the effect of solar radiation on the window temperature and participants.

Table 2: Boundary conditions: set surfaces' temperatures

Walls' temperatures [°C]	**Floor temperature [°C]**	**Ceiling temperatures [°C]**	**Window temperature [°C]**	**Exterior wall under the window [°C]**
20	20	28, 35	Passive surface: variable by the outdoor and indoor conditions	Passive surface: variable by the outdoor and indoor conditions

(a) (b)

Figure 3: The ‘LOBSTER’ test facility: a) view from outside, b) View into one of the two offices at the LOBSTER

2.3. Measurements

Thermal environmental parameters including the air temperature, air humidity, air velocity and the globe temperatures were measured by Ahlborn stress meter with the time-resolution of 1 min at four different heights of 10, 60, 110 and 170 cm close to the occupants (see Figure 4). These heights include the occupant zone for a sedentary person (ASHRAE-55, 2017). Indirect method based on view factors and temperatures of surrounding surfaces (Romana *et al.*, 2013) was also used for calculation of mean radiant temperatures in asymmetric conditions.

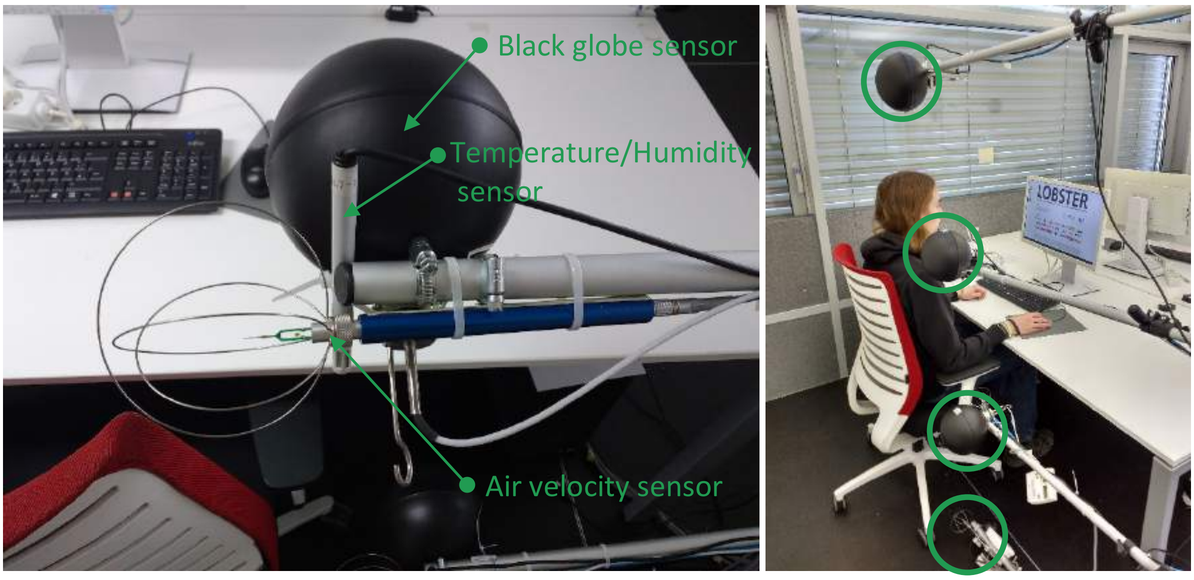


Figure 4: Sensors (air temperature/humidity, air velocity and globe temperature) and their positions at 10, 60, 110 and 170 cm from the floor

The effect of skin temperature on the local thermal comfort and sensation and the influence of ceiling heating system on the skin temperatures are assessed in this study. Skin temperatures were measured at 8 body-points. Table 3 presents the measuring points and the corresponding weighting factors introduced by ISO 9886 standard (ISO-9886, 2004). The local skin temperatures were measured using iButton sensors (DS1921H-F5) with time-resolution of 1 min.

Table 3: Weighting factors for calculation of the mean skin temperature (8-point weighting) (ISO 9886 2004)

Forehead	**Right scapula**	**Left upper chest**	**Right upper arm in upper location**	**Left upper arm in lower location**	**Left hand**	**Right anterior thigh**	**Left calf**
0.07	0.175	0.175	0.07	0.07	0.05	0.19	0.2

3. Experimental results and subjective responses

Table 4 presents the thermal environmental parameters and their average values at the height of 110 cm and the average temperatures of boundary conditions in four different experimental scenarios. As given in Table 4, the thermal environmental parameters have almost identical values at equal ceiling temperatures regardless of the distance of sensors to the window in scenarios -1 and -4 or in scenarios -2 and -3. Beyond the expectation, the internal surface of the window was relatively warm. It is because that the U-Value of the window was about 1.2 W/K.m^2 and the internal surface of window absorbed radiation from internal room surfaces, particularly from the warm ceiling. The reason for the notable temperature difference of the external wall between the first two scenarios to the second two scenarios is the heat from the computers. In the second two scenarios, the computers were located near to the external walls; therefore, the heat from the computers heated the sensor slightly.

Table 4: Average values of the measured indoor environmental parameters at the height of 110 cm and average of room surface temperatures in four scenarios. CT and DW stand for the ceiling temperature and distance to the window, respectively.

Variables		**Scenario-1 (CT: 35 °C DW: 3 m)**	**Scenario-2 (CT: 30 °C DW: 3 m)**	**Scenario-3 (CT: 30 °C DW: 1 m)**	**Scenario-4 (CT: 35 °C DW: 1 m)**
Thermal enviromental parameters	Operative temperature [°C]	23.1	21.6	21.4	23.4
	Air temperature [°C]	22.7	21.3	21.3	22.9
	Mean radiant temperature [°C]	23.2	21.8	21.5	23.6
	Air velocity [m/s]	0.051	0.048	0.040	0.033
	Relative humidity (%)	34.7	30.7	31.9	30.7
Boundary conditions	Left wall temperature [°C]	20.8	20.4	20.3	20.8
	Right wall temperature [°C]	20.3	20.1	19.9	20.5
	Back wall temperature [°C]	20.6	19.9	20.3	20.4
	Floor temperature [°C]	20.3	19.8	20.1	20.8
	Exterior wall temperature [°C]	19.3	19.7	21.8	23.0
	Window temperature [°C]	18.8	17.5	17.7	20.2

3.1. Thermal sensation analysis

Figure 5 presents the percentage of overall and local thermal sensation votes acquired in four different experimental scenarios described in

Table 1. The effect of ceiling temperature on the participants’ votes who sat at the distance of 3m to the window was tested in scenario-1 and -2, and the effect of ceiling temperature on the participants sitting at a distance of 1m to the window was tested in scenario-3 and -4. By paying attention to the overall thermal sensation votes related to all four scenarios, we can realize that the majority of votes lay between “slightly cool, -1” and “slightly warm, +1”. The participants felt slightly cooler in the scenario-2 and -3 where the ceiling temperature was 28 °C. As seen, the overall thermal sensation votes follow the local votes at the upper-body parts, and the cold thermal sensation votes at the extremities like hands and feet have less impact on the cold votes for the overall thermal sensation. This is in accordance with the findings obtained by Arens (Arens *et al.*, 2006) for the local cooling of body parts.

The unfamiliarity of participants with the experimental test-room and the voting method may influence the accuracy of votes in the 1st week to some extent. Additionally, the temperature of external walls was relatively cold in the 1st scenario compared to the other scenarios. Due to these two possible reasons, the local votes at some lower limbs in the 1st scenario do not follow the trend of votes seen in other scenarios.

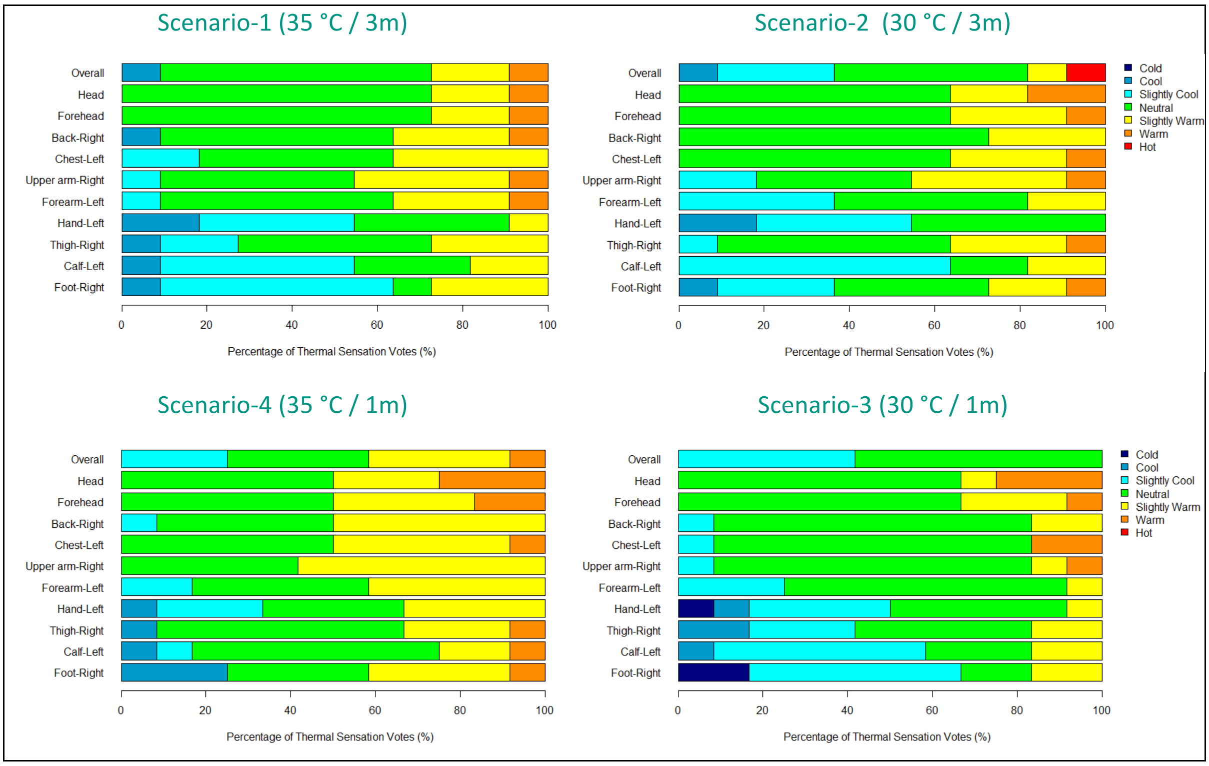


Figure 5: Percentage of overall and local thermal sensation votes in response to four different experimental scenarios. List of scenarios is given in Table 1.

A comparison between the graphs related to four scenarios shown in Figure 5 reveals that participants felt warmer at upper-body parts for higher ceiling temperatures in scenario-1 and -4. The local votes at hand, forearm and lower-body parts were cooler for the ceiling temperature of 28 °C in the scenario-2 and -3 compared to the other two scenarios. In response to the ceiling temperature of 35 °C, in the 1st scenario, more than 50% of participants voted “cold, -3”, “cool, -2” and “slightly cool, -1” to the lower-body parts and hand. In contrast, in the 4th scenario, the participants felt warmer at most of the body parts, particularly at extremities. It is because the temperatures of external wall and window in the 4th scenario were higher than the temperatures in the 1st week (see Table 4).

It is important to mention that although the surface temperatures of window and external wall in the 3rd scenario were slightly higher than the surface temperatures in the 2nd scenario, the participants felt cooler for the 3rd scenario where the distance to the window was 1 m. One possible reason can be that the close distance to the window created perceived cooler thermal sensation despite its higher surface temperature.

Figure 6 presents the average of overall and local thermal sensation votes for each scenario. As seen, in general, the overall and local sensation have the highest values in the scenario-4 (brown line) and have the lowest votes in the scenario-3 (green line). The average values of overall thermal sensation are in the neutral zone [-0.5 and +0.5]. The average values of votes at the upper-body parts (except hand and forearm) lay between "neutral, 0" and "slightly warm, +1", and the lower parts (except thigh) have negative values between "neutral, 0" and "slightly cool, -1". The head has the highest average value of votes compared to the other limbs with a maximum value of "0.8" which is about slightly warm. The coldest parts are feet and hands with the minimum values of "-0.8" which is about slightly cool. These results appear to confirm that the radiant ceiling heating system operating at even low temperatures (28 °C – 35 °C) can provide fairly neutral thermal sensation at the majority of body parts in a new or an energy-renovated building having a standard window and a façade with rather low U-values.

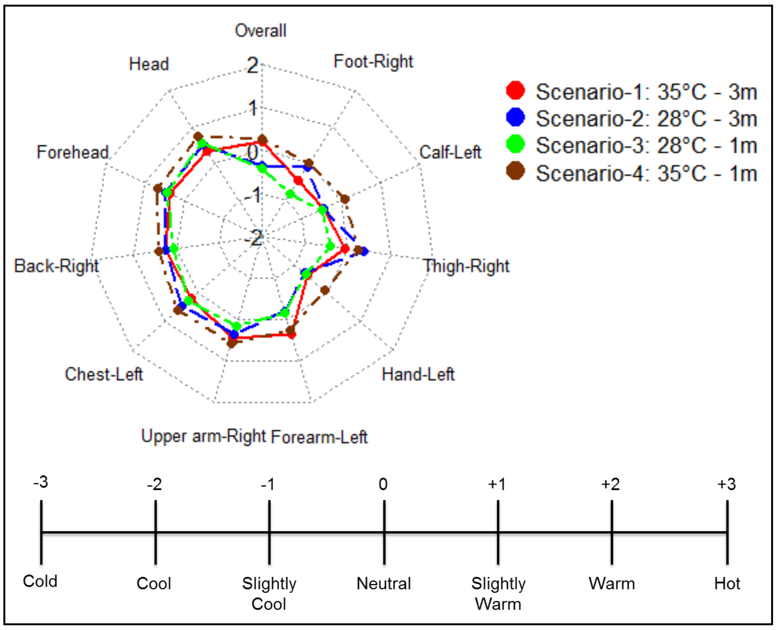


Figure 6: Average of overall/local thermal sensation votes in four different experimental scenarios. List of scenarios is given in Table 1.

Figure 7 shows the relation between the average of local thermal sensation votes and the average of skin temperatures at 8 points (excluding the top of the head and foot), and the relation between the overall thermal sensation and mean skin temperature. In all four scenarios, the thermal sensation votes follow the skin temperatures at all points in each body zone including head zone, chest/back zone, hand/arm zone and leg zone that are shown in different colours. The findings of a former study show that the slight changes in the skin temperature can influence the thermal sensation significantly (Sakoi *et al.*, 2007). This statement can support the connection of local sensation votes and skin temperatures shown in Figure 7. As seen, the effect of skin temperature on the thermal sensation is noticeable at the extremities including hand and foot and the limbs near to these parts. For instance, the slight changes of skin temperature from the upper arm to the forearm and then from the forearm to the hand or from thigh to the calf result in significant changes of thermal sensation. The head (forehead) is an upper extremity and is sensitive to the warm environment and warm skin temperature. As seen, although forehead's temperature is relatively lower than the temperature at the back, it feels warmer than the back. The upper chest and upper back have the highest skin temperatures. The reason is that the large body surfaces at the upper back and the upper chest were exposed to the warm ceiling. However, it is interesting to see that despite a small skin temperature difference between the back and chest, the difference in local sensation votes is notable. The measurements clearly indicate that the back is more sensitive to the changes in skin temperature compared to the chest. Leaning back to the chair's backrest and possible sweating, and separation of the back from the backrest and evaporation can influence the local thermal sensation votes and skin temperature at the back. The effect of local cooling and warming of the chest and the back on the local votes was investigated by Arens et al. (Arens *et al.*, 2006). They proved that the local cooling of back and chest influence the local and global thermal sensation and comfort significantly. However, to the knowledge of authors, the difference between thermal sensitivities of the back and the chest in asymmetric thermal environments with radiant heating systems has not been studied. This could be done in future work.

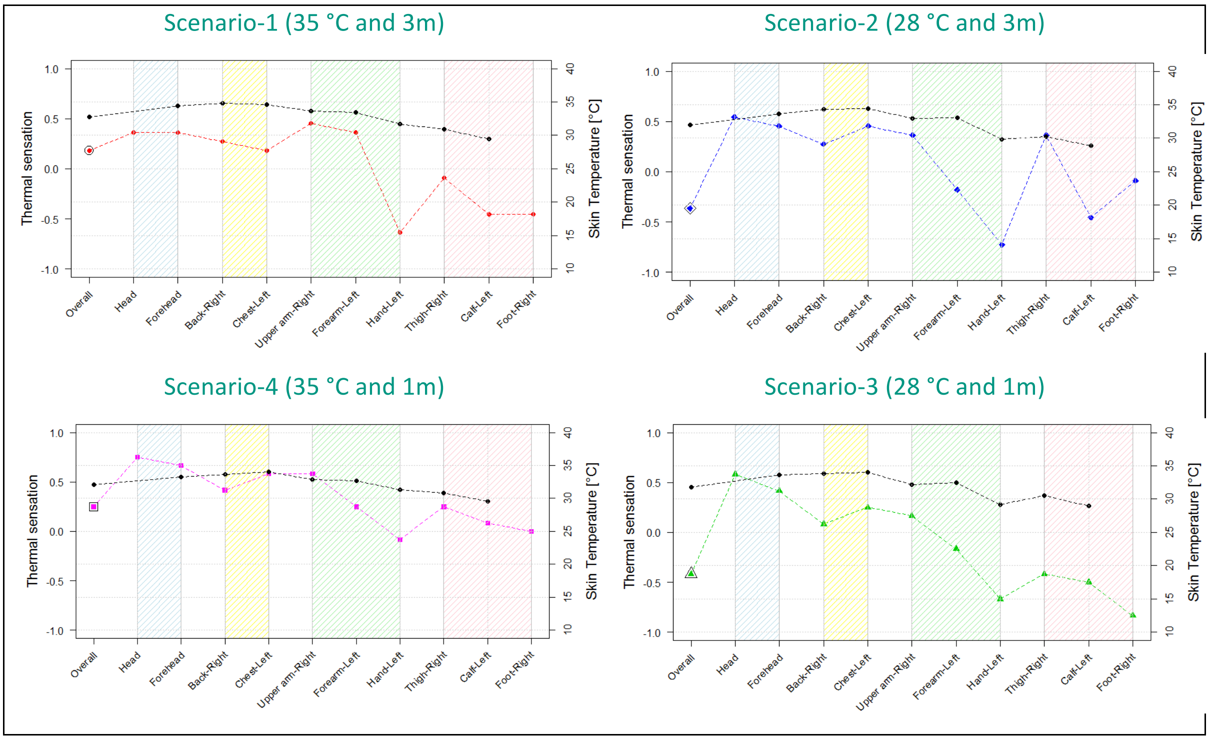


Figure 7: Average of overall and local thermal sensation votes and an average of skin temperatures in four different experimental scenarios. List of scenarios is given in Table 1. The black circle points are the average of local and overall skin temperatures.

The former studies (Gagge *et al.*, 1967; Sakoi *et al.*, 2007) experimentally proved that the overall thermal sensation votes reach the neutral conditions at the mean skin temperature of about 33.5 °C. In contrast, Figure 7 shows that the overall thermal sensations of four scenarios are in the neutral zone [-0.5, +0.5] when the skin temperature is between about 32 and 33 °C. The reason can be different experimental conditions such as room air temperatures, draught, clothing insulation (clo), and type of heating systems. For instance, while the room air temperature in the study of Sakoi et al. (Sakoi *et al.*, 2007) was about 26 °C, the room air temperature in the LOBSTER was between 21 and 23 °C.

The highest skin temperature difference is between the calf and the forehead (temperatures at head and foot are not measured), which is the result of large asymmetric temperature between the floor (about 20 °C) and the ceiling (28 and 35 °C). This skin temperature difference is a reason for the large difference of local thermal sensation between the calf and the forehead. Although the hands received the radiation from the warm ceiling and they are relatively far from the cool floor, participants voted cooler at hand compared to the calf and foot. Zhang (Zhang, 2003) mentioned in her thesis that the hand is possibly the most sensitive part of a body with regard to the body's thermoregulation, and it is particularly sensitive to the cooling process.

3.2. Local thermal comfort analysis

Figure 8 presents the percentage of overall and local thermal comfort votes acquired in four different scenarios. As seen, the local thermal votes for the upper limbs are dominant in defining the overall comfort. The comparison between the percentage of thermal comfort votes in Figure 8 and the percentage of thermal sensation votes in Figure 5 shows that the number of "about uncomfortable" votes given to the upper limbs are probably associated with the "slightly warm" and "warm" votes. In contrast, the participants gave the highest number of "uncomfortable" and "about uncomfortable" votes to the foot, calf, thigh and hand that can be related to the relatively high number of "cold" and "cool" sensation votes at these limbs. Figure 8 indicates that although the head is the most sensitive part to warm environments and closest part to the warm ceiling, it is the most comfortable limb. Influence of low outdoor temperatures on perceived comfort temperatures may explain the relation between the highest number of "warm" sensation votes (see Figure 5) and the highest number of "comfortable" votes to the head.

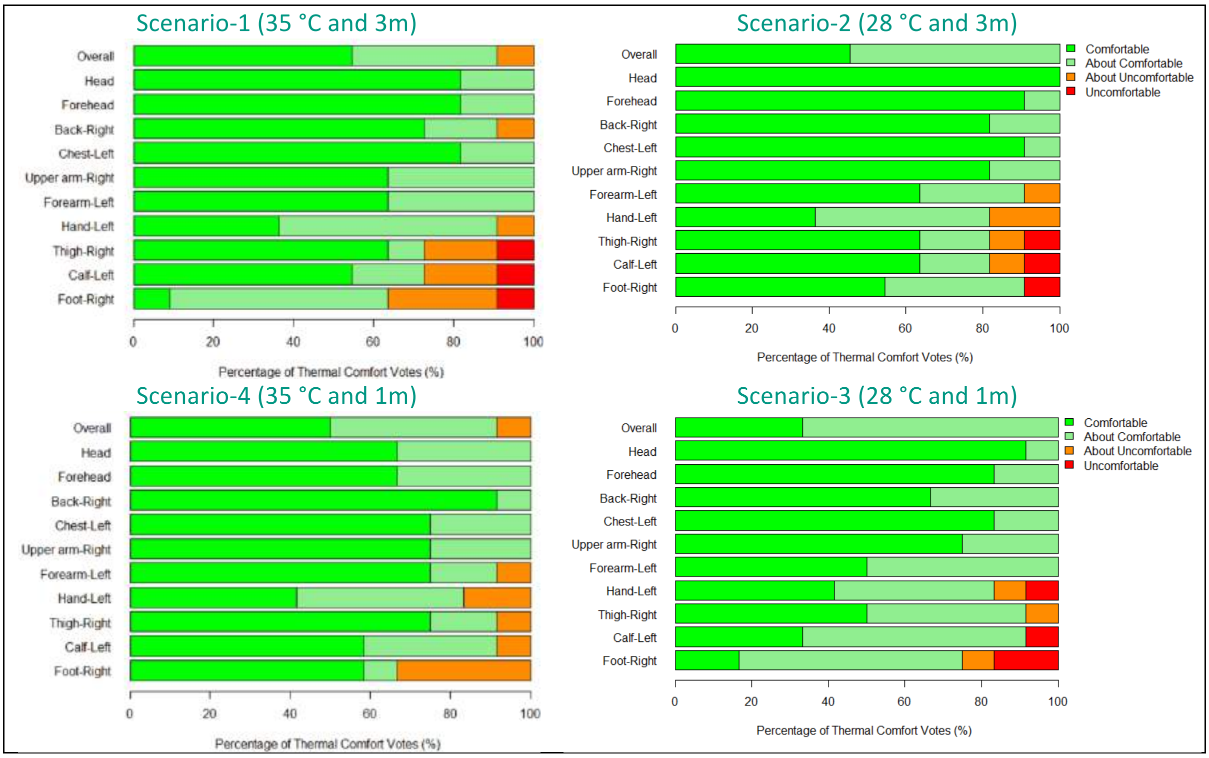


Figure 8: Percentage of overall and local thermal comfort votes in four different experimental scenarios. List of scenarios is given in Table 1.

The figures clearly indicate that almost all participants felt “comfortable” and “about comfortable” at the upper-body limbs except hand, and approximately more than 70 % of the participants felt “comfortable” and “about comfortable” at the hand and lower limbs except foot. The results imply that the ceiling heating system operating at relatively low temperatures (28 and 35 °C) can provide comfortable conditions for all occupants if the temperatures of façade and window are more than 17 °C and temperatures of other surfaces are at least 20 °C. To achieve these relatively high surface temperatures, the building envelope should satisfy the low U-values recommended by new building regulations.

Figure 9 presents the average of overall and local thermal comfort votes for each scenario given in Table 1. The figure clearly shows that the average of all overall and local thermal comfort votes for all scenarios (except votes at the foot in scenario-1 and -3) are more than “+2.0” (“slightly comfortable” and “comfortable”), and that the majority of participants have a very pleasant condition (> +2.5) at the upper limbs. These results prove that the majority of participants were satisfied with the indoor environment that a low-temperature ceiling heating system operating at low temperatures (28°C - 35°C) provides. Analyses of data show that at each scenario, participants had almost equal comfort perception at the upper limbs (except the hand). In contrast, the participants had wide comfort awareness at the lower limbs and hand. Likewise the thermal sensation results shown in Figure 6, the local comfort votes at the upper limbs had the highest impact on the overall thermal comfort, which kept the overall comfort in the “comfort” condition.

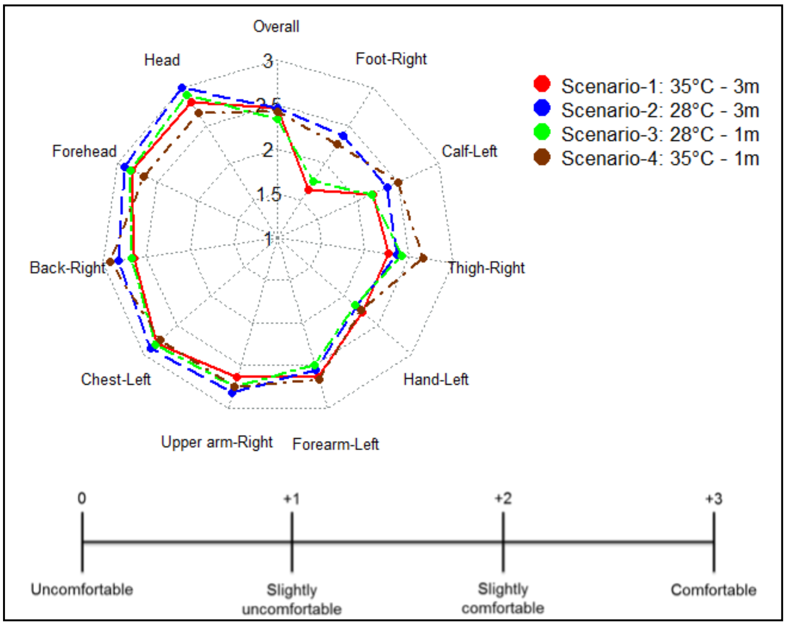


Figure 9: Average of overall/local thermal comfort votes in four different experimental scenarios. List of scenarios is given in Table 1.

Figure 10 presents the average of overall/local thermal comfort votes at 10 points and the mean of skin temperatures at 8 points (see section 2.3) for each of four scenarios. As seen, the local thermal comfort votes at the selected 8 points closely follow the local skin temperatures. However, a slightly different trend was observed with the back compared to the chest in yellow areas and with the forearm compared to the upper arm in green areas. For instance, in the 2nd and 3rd scenarios, the comfort votes for the back are lower than for the chest for only slightly lower skin temperatures; and in 1st and 4th scenarios, the votes for the back behave differently in association to the skin temperature difference between the back and the chest. The existing backrest of the chairs may influence the skin temperature and the local comfort votes. Concerning the forearm, despite small skin temperature difference between the upper arm and forearm, there is a noteworthy difference for the thermal comfort votes. It is because of the fact that the thermal perception of the hand influences the participants' awareness at the forearm and its influence is stronger in a cooler environment.

The comparison between Figure 10 and the thermal sensation votes shown in Figure 7 indicates that the overall thermal comfort follows closely the mean skin temperature, which is not seen in the thermal sensation votes shown in Figure 7. Although the thermal sensation at the hand and calf was very much sensitive to the local skin temperatures, the comfort votes at these parts change mildly. Additionally, despite the significant difference between the thermal sensation votes at the lower and upper limbs, the comfort votes are fairly close. It confirms that the participants were less sensitive to the thermal comfort conditions compared to the thermal sensation even at the cool/cold zone near to the floor.

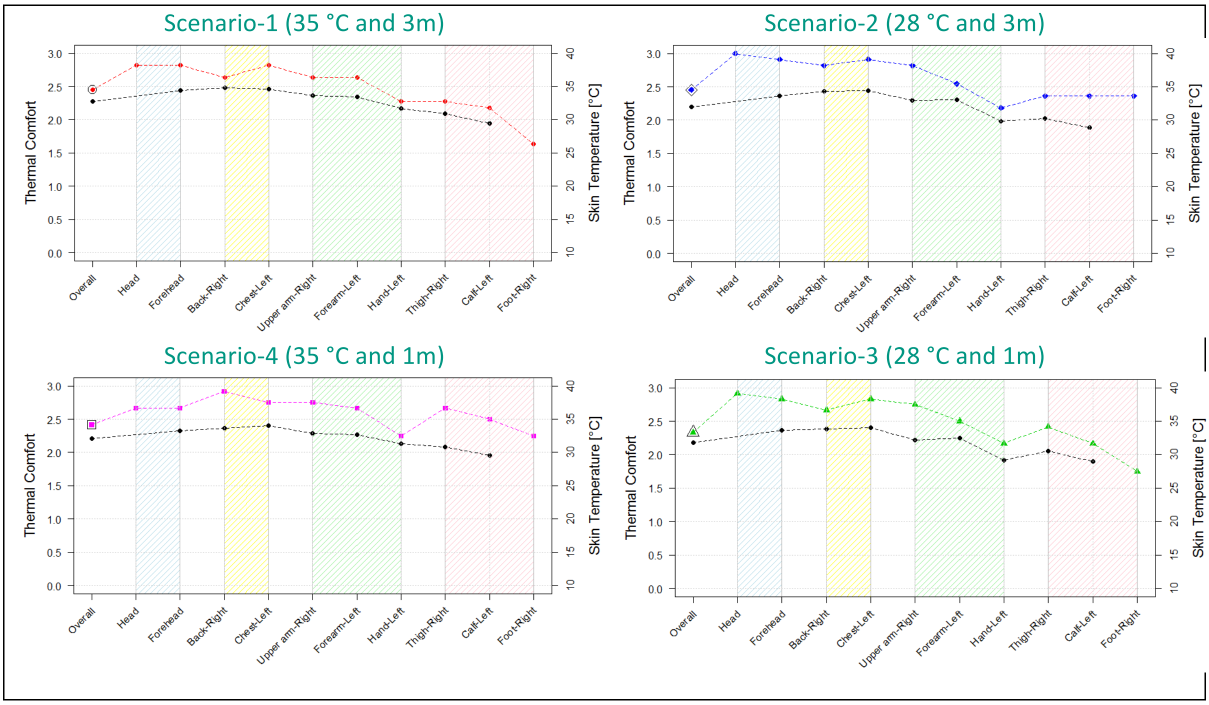


Figure 10: Average of overall and local thermal comfort votes and an average of skin temperatures in four experimental scenarios. List of scenarios is given in Table 1. The black circle points are the average of local and overall skin temperatures.

4. Summary

In the present study, the potential application of a low-temperature radiant ceiling system in new and energy-renovated buildings was evaluated based on the comfort criteria. An experimental study with 14 participants was performed in an indoor climate test facility. From the research that has been carried out, the following key findings can be drawn:

- overall, the results imply that the ceiling heating system operating at low temperatures (28 and 35 °C) can provide mostly 'neutral' overall thermal sensations at two positions in respect to the window (1m and 3m) if ,according to advanced building energy-efficiency regulations, a window with a U-value below 1.3 W/K.m^2 as well as external walls and floor with U-values of about 0.3 W/K.m^2 are used;

- the overall thermal sensation votes followed the local votes at the upper-body parts, and the cold thermal sensation votes at the extremities like hands and feet had less impact on the cold votes for the overall thermal sensation;
- beyond the expectation, the head was perceived as the most comfortable body part, even though the head was the closest body-part to the warm ceiling and it is the most sensitive upper extremity to the warm condition;
- in this study, the lower-body limbs and hand were the least comfortable limbs;
- the analysis of data showed that at each scenario, participants had almost equal comfort perceptions at the upper limbs. In contrast, the participants had a wide range of comfort awareness at the lower limbs and hand for different scenarios;
- the results revealed that the overall thermal comfort followed closely the mean skin temperature, which was not seen in the thermal sensation votes. Although the thermal sensations at the hand and calf were very much sensitive to the local skin temperatures, the comfort votes at these parts changed mildly. Additionally, despite the significant difference between the thermal sensation votes at the lower and upper limbs, the comfort votes were fairly close. It confirmed that the participants were less sensitive to the thermal comfort conditions compared to the thermal sensation even at the cool/cold zone near to the floor.

Further experiments with 53 subjects have been performed in November and December 2017 in order to resolve remaining issues such as the development of a comfort models for asymmetric conditions created by radiant systems and validation of CFD models. The results will be presented in future papers.

5. Acknowledgement

This work was supported by the Federal Ministry for Economic Affairs and Energy, BMWi, under the project No. 03SBE0001 A (LowEx-Bestand). The authors wish to acknowledge the assistance of Dr. Schweiker and Mr. Kleber in regards to preparation of documents for the ethics and the data protection commissions of KIT, and designing the questionnaires.

6. References

Arens, E., Zhang, H. and Huizenga, C. (2006) 'Partial- and whole-body thermal sensation and comfort, Part II: Non-uniform environmental conditions', *Journal of Thermal Biology*, 31(1–2 SPEC. ISS.), pp. 60–66. doi: 10.1016/j.jtherbio.2005.11.028.

ASHRAE-55 (2017) 'ANSI/ASHRAE Standard 55-2017: Thermal environmental conditions for human occupancy', *ASHRAE*. ASHRAE.

Fanger, P. O. *et al.* (1980) 'Comfort limits for heated ceilings', *ASHRAE Transactions*, 86(2596), pp. 141–156.

Gagge, a. P. P. *et al.* (1967) 'Comfort and thermal sensations and associated physiological responses at various ambient temperatures', *Environmental Research*, 1(1), pp. 1–20. doi: 10.1016/0013-9351(67)90002-3.

Griffiths, I. and McIntyre, D. (1974) 'Subjective Response to Overhead Thermal Radiation', *Subjective Response to Overhead Thermal Radiation*, 16(4), pp. 415–422. doi: 10.1177/001872087401600409.

Huizenga, C. *et al.* (2006) *Window Performance for Human Thermal Comfort*, *National Fenestration Rating Council*. Berkeley.

ISO-9886 (2004) *9886: 2004, Ergonomics–Evaluation of thermal strain by physiological measurements*, *CEN-European Committee for Standardization*.

McNall, P. and Biddison, R. (1970) '1970 Thermal and comfort sensations of sedentary persons exposed to asymmetric radiant fields.pdf', *ASHRAE Transactions*, 76(1).

Nilsson, H., Brohus, H. and Nielsen, P. (2007) 'CFD modeling of thermal manikin heat loss in a comfort evaluation benchmark test', *Proceedings of the Roomvent 2007*, (June). Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.424.218&rep=rep1&type=pdf.

Palzer, A. and Henning, H.-M. (2014) 'A Future German Energy System with a Dominating Contribution from Renewable Energies: A Holistic Model Based on Hourly Simulation', *Energy Technology*, 2(1), pp. 13–28. doi: 10.1002/ente.201300083.

Romana, F. *et al.* (2013) 'On the measurement of the mean radiant temperature and its influence on the indoor thermal environment assessment', *Building and Environment*, 63, pp. 79–88. doi: 10.1016/j.buildenv.2013.01.026.

Sakoi, T. *et al.* (2007) 'Thermal comfort, skin temperature distribution, and sensible heat loss distribution in the sitting posture in various asymmetric radiant fields', *Building and Environment*, 42(12), pp. 3984–3999. doi: 10.1016/j.buildenv.2006.10.050.

Wagner, A., O'Brien, W. and Dong, B. (2017) *Exploring Occupant Behavior in Buildings*. Edited by A. Wagner, W. O'Brien, and B. Dong. Springer International Publishing AG.

Wyon, D. P. *et al.* (1989) 'Standard procedures for assessing vehicle climate with a thermal manikin', *SAE Technical Paper*. SAE Technical Paper.

Zhang, H. (2003) *Environments, Human thermal sensation and comfort in transient and non-uniform thermal enviroments*, *Center for the Built Environment UC Berkeley Peer*. doi: 10.1080/09613218.2011.556008.

Zhang, H. *et al.* (2010) 'Thermal sensation and comfort models for non-uniform and transient environments: Part I: Local sensation of individual body parts', *Building and Environment*, 45(2), pp. 380–388. doi: 10.1016/j.buildenv.2009.06.018.

Zhang, H. and Huizenga, C. (2006) 'Partial- and whole-body thermal sensation and comfort - Part I: Uniform environmental conditions', *Journal of Thermal Biology*, 31(1–2 SPEC. ISS.), pp. 53–59. doi: 10.1016/j.jtherbio.2005.11.028.

Comparing occupant thermal perception of air conditioning and ceiling-mounted radiant cooling panels coupled to a roof pond

Eduardo Krüger[1], Leandro Fernandes[1], Wolfgang Mutsafi-Haller[2], Evyatar Erell[2]

[1] Universidade Tecnológica Federal do Paraná, Curitiba, Brazil, ekruger@utfpr.edu.br, fernandes.ufpr@gmail.com
[2] Ben-Gurion University of the Negev, Israel, erell@bgu.ac.il, womoha@post.bgu.ac.il

Abstract: An experimental study compared the thermal response of subjects in two test rooms, one of which was cooled by a roof pond coupled to radiant cooling panels and the second by a conventional split AC unit. Measurements of the surface temperatures indicated that structural cooling and thermal stabilization were obtained in the roof pond room, whereas in the air-conditioned room thermal control was achieved only within the short period of the session through air temperature changes. For similar air temperature, there was a slight preference for the roof pond room, which had a lower Mean Radiant Temperature. The roof pond room was found to be more effective in ensuring comfort conditions continuously and without occupant intervention.

Keywords: roof pond, passive cooling, radiant cooling, thermal comfort, questionnaire survey.

1. Introduction

Roof pond systems can improve indoor comfort under certain conditions, particularly in single-storied buildings, through several mechanisms, including thermal stabilization, structural cooling and significant lowering of daytime indoor air and surface temperatures. Water-based radiant cooling systems, when coupled with a roof pond, can further improve thermal performance, due to reduced distribution losses (Li et al., 2015). Unlike standard air-conditioning systems, the main driver is heat transfer by radiation, with limited air movement. Tests in an experimental house, built in Rennes, France, showed that two thirds of summer cooling using radiant cooling panels occurred by radiation and only one third by convection (Miriel et al., 2002). Consequently, the ASHRAE definition for Radiative Heating and Cooling systems (RHC) is that radiant heat transfer covers more than 50% of heat exchange within a conditioned space (ASHRAE, 2012).

Radiant cooling systems reduce draught discomfort due to reductions in air movement. Babiak et al. (2009) identify two types of systems that use water as heat-carrier when the heat exchange within the conditioned space is more than 50% radiant: 1) low thermal inertia systems, including suspended ceiling panels; and 2) high thermal inertia systems, including Thermally Activated Building Systems (TABS), where pipes are embedded into the building envelope.

Imanari et al. (1999) compared the thermal comfort performance of two cooling operation modes of a meeting room: a suspended radiant ceiling panel and an air-handling unit (AHU) simulating a conventional all-air cooling system. Thermal conditions (PMV) in the room were set to within ±0.5 of neutral. Comfort surveys were administered during meetings to male subjects, without them knowing which operation mode is under use, in order to evaluate the room's overall thermal conditions. Results showed that the radiant cooling mode yielded a higher percentage of positive comfort votes when compared to the AHU with humidity control - even though thermal conditions were set to be equivalent.

Recently, Meggers et al. (2017) presented the concept of their Thermo-heliodome, an experimental pavilion located at Princeton University that 'cools without air conditioning'. The system operates using indirect evaporative cooling (a nearby evaporative tower supplies water chilled to nearly wet-bulb temperature) and radiant cooling panels with chilled pipes. An occupant comfort survey on a late summer day showed that despite negligible differences in air temperature, most of the participants lowered their estimate of the prevailing air temperature inside the facility, reflecting the perceived coolness which was in fact due to effective radiant cooling.

There have been few field studies to date of occupant perceptions of radiant vs. convective cooling (Mustakallio et al., 2017). A review paper by Karmann et al. (2017) reported that very few studies were found which were based on occupant feedback in real buildings. Of the 73 papers reviewed, after applying exclusion criteria, only two studies remained that focused on occupant-based comfort surveys comparing radiant vs. convective cooling systems (Shellen et al., 2012, Shellen et al., 2013). Results however were found to be inconclusive regarding which of the systems had a higher performance in terms of occupant comfort perception.

In summer conditions, a roof pond system can benefit from the process of evaporation, the phase-change cooling of the wetted surface. The pond's water temperature will be typically close to the average wet-bulb temperature and the ceiling, cooled by the pond, acts as a heat sink to the space below it. Studies on roof ponds, as recently surveyed by Sharifi & Yagamata (2015), focus on system performance and optimization, pointing to a shortage of research on the effect of such systems on thermal perception indoors. A cross search in the SCOPUS database, with search items 'roof pond' and 'participants' or 'respondents' or 'questionnaire survey' yields no results.

The objective of this study was to address the afore-mentioned shortcomings, comparing occupant thermal sensation in a room cooled by ceiling radiant cooling panels coupled with a roof pond to sensation in a similar room cooled with a conventional air-conditioning system. Overall, the study serves the purpose of testing a given thermal environment under two different cooling strategies: passively, by means of the combination of thermal mass, evaporative and radiant cooling (ceiling radiant cooling panels provided with chilled water cooled by a roof pond); and conventional air-conditioning. In the latter case, cooling is achieved more quickly in terms of air temperature, whereas in the roof pond room temperature is maintained throughout the whole period of exposure and monitoring.

2. Methodology

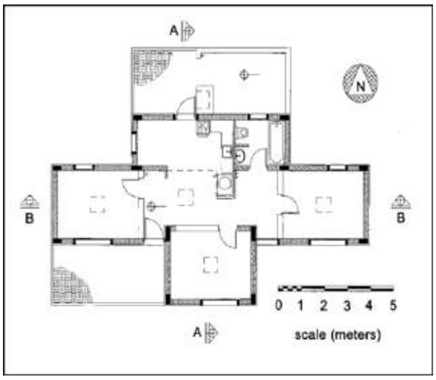
The study was carried out in a laboratory building with two nearly identical rooms, one equipped with a roof pond and the second with a conventional split air conditioning unit. In the first stage of the experiment, different configurations of the roof pond were tested, to identify the most effective means of providing chilled water and cooling the ceiling. During the second stage, thermal conditions in the test rooms were monitored by an electronic data acquisition system and evaluated by subjects, who spent some time in both rooms and provided feedback through questionnaires.

2.1. Test facility

The test rooms are part of an experimental building located at the Sde-Boqer Campus of Ben-Gurion University of the Negev, in Midreshet Ben Gurion, Israel (Latitude 30.8°N, Longitude 35°E and elevation 478 meters). The climate is characterized by strong daily and seasonal thermal fluctuations, dry air and clear skies with intense solar radiation. In summer, average daily maximum temperature is 32°C and average daily minimum is 17°C. Global horizontal radiation averages 7.7kWh/m² per day during June and July (Bitan and Rubin, 1991).

The test building (Figure 1) was constructed in 1991 for experiments in passive cooling and solar control (Erell et al., 1992 and Erell and Etzion, 1999). It incorporates three nearly identical test rooms 270 cm wide, 350 cm long, and 305 cm in height, with white-painted interior. The east room is covered by the roof pond whereas the middle one (to the south) was fitted with a split AC unit. To reduce the possibility of inadvertent bias because of the sight of the AC unit, the evaporator of a similar AC unit was used as a fan in the passive test room, closely resembling the AC equipment used in the other room but providing no cooling.

a)



b)

Figure 1 – Test building: a) south facade and b) plan view

The windows consist of three sections: a central section (114 cm in height), a lower section with fixed glazing (42.5 cm in height), and an upper section, which is also fixed (62 cm in height). The window width (net) is 134 cm and the sill depth is 25 cm. During experiments, in order to avoid heat gains from direct and reflected sunlight, only the lowest pane remained unobstructed, the other panes were blocked off by external roll-down blinds.

Two aluminum radiant cooling panels were suspended from the ceiling in the roof pond room, each with a 1.6m² surface area. The water from the pond was circulated through the panels by a small electric pump.

2.2. Test Configurations

The study was carried out during summer months in 2017. An initial period of tests with the passive system was carried out to determine the best configuration of the roof pond. Configurations tested for the Roof Pond (RP) room were the following:

1. Base case, with conventional flat roof (insulated concrete slab), monitored during eight days (June 17-24);
2. Conventional flat roof, shaded, monitored during 10 days (June 26 through July 7);
3. Same as Configuration 2, with roof pond with circulation of water, monitored during nine days (July 10-18);
4. Same as Configuration 3, shaded and with floating insulation polystyrene boards, monitored during three days (July 22-24);
5. Same as Configuration 4, with nighttime spraying, monitored during three days (July 26-28);
6. Same as Configuration 5, but with 24-h spraying, monitored during July 9 through September 5.

Figure 2 shows Configuration 6, which was later used during the occupant response sessions.

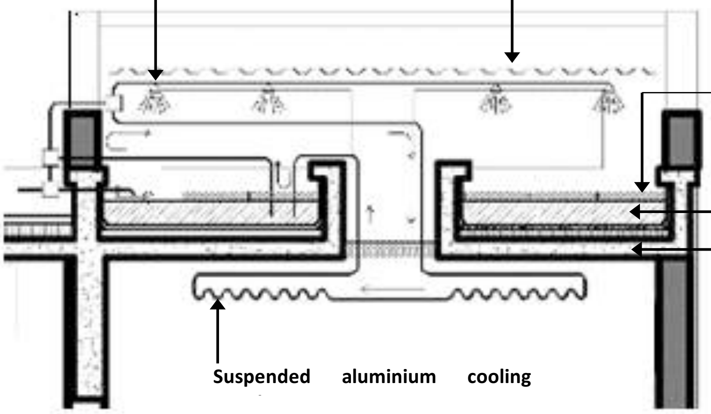


Figure 2 – Configuration 6 of the Roof Pond, with permanent spraying and water circulation in the ceiling radiative panels

The choice of the best configuration for the thermal sensation tests was based on three criteria: a) the smallest thermal fluctuation, given by the decrement factor (f); b) the highest temperature reduction during peak hours; and c) the lowest mean indoor temperature, given by the Mean Temperature Deviation Factor (MTD).

The decrement factor is given as:

$$\mathbf{f} = \frac{(\mathbf{T_{max}} - \mathbf{T_{min}})_{\mathbf{int}}}{(\mathbf{T_{max}} - \mathbf{T_{min}})_{\mathbf{out}}} \qquad \text{(Eq.1)}$$

Where $(\mathbf{T_{max}} - \mathbf{T_{min}})_{\mathbf{int}}$ and $(\mathbf{T_{max}} - \mathbf{T_{min}})_{\mathbf{out}}$ are the daily indoor and outdoor temperature fluctuations, respectively.

The daily Mean Temperature Deviation factor (MTD) indicates whether over a 24-hour cycle the net effect of the roof pond indoors was heating (positive outcome) or cooling (negative values). It can be expressed as follows:

$$\mathbf{MTD} = \left(\frac{\mathbf{T_{int\,avg}} - \mathbf{T_{out\,min}}}{\mathbf{T_{out\,avg}} - \mathbf{T_{out\,min}}}\right) - \mathbf{1} \qquad \text{(Eq.2)}$$

Where $\mathbf{MTD}$ is the daily Mean Temperature Deviation factor, $\mathbf{T_{in\,avg}}$ is the indoor average temperature, $\mathbf{T_{out\,min}}$ is the minimum outdoor temperature, $\mathbf{T_{out\,avg}}$ is the outdoor average.

2.3. Monitoring

Outdoor conditions were obtained from the local meteorological station (located about 800 meters north of the test building) with the following variables: dry bulb temperature, wind speed, incoming solar radiation and relative humidity. During test days, indoor air and surface temperatures were recorded by Type T thermocouples. Globe temperature was likewise measured by thermocouples, inserted in a sphere of 40mm diameter (ping-pong ball), painted grey (RAL 7001). Relative humidity was measured with Vaisala HMP-60 Temperature/Relative Humidity sensors and air velocity with Kurz Portable Air Velocity Meters (Series-441). Surface temperature of the ceiling, floor, walls, radiant cooling panels (only in the roof pond room) and at two heights of the window panes were recorded. In both rooms, air temperature was measured at four different heights (10 cm, 60 cm, 110 cm and 280 cm). Relative humidity, air velocity and globe temperature were recorded at 60 cm height, corresponding to a seated position as shown in ISO 7726. All sensors were connected to a Campbell Scientific data logger CR23X via a Multiplexer AM-32. Readings were made every 30 seconds, and averages calculated at 10 minute intervals.

Also measured, parallel to indoor measurements, were roof pond water temperature and ambient air temperature just above the water surface.

2.4. Questionnaire

Participants were recruited as volunteers among students and staff of BGU. The participants spent approximately 30-35 minutes each in the building, first in one room (30 minutes), then in the second (an additional 5 minutes). During experiments, participants filled out thermal comfort questionnaires (printed copies) three times. The times designated for filling out questionnaires are shown in Figure 3.

Time stamp 1	Time stamp 2	Time stamp 3
within the first 5 minutes upon arrival	after 30 minutes	within the first 5 minutes upon arrival
OFFICE 1	OFFICE 1	OFFICE 2

⟵ COMPARISONS BETWEEN OFFICES ⟶ (Time stamp 2 – Time stamp 3)

Figure 3 – Time schedule for filling out questionnaires

The questionnaire, constructed according to guidelines of International Standard ISO 10551, consisted of personal data (biometrics, time of residency in Israel, country of origin, previous thermal environment/transport mode to the test building), clothing information (look-up table) and questions on thermal perception at three time stamps. Personal data were filled out at the start while clothing insulation was estimated visually by the researchers.

The thermal perception was assessed by three metrics, corresponding to the three questions below: thermal sensation (TS), thermal comfort (TC) and thermal preference (TP). Subjects were asked to indicate their responses on a 7-point Likert scale (Figure 4).

What is your general thermal sensation right now?

( )	( )	( )	( )	( )	( )	( )
-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

How do you feel about the thermal environment?

( )	( )	( )	( )	( )
0	1	2	3	4
Very uncomfortable	Uncomfortable	Neutral	Comfortable	Very comfortable

At this moment, would you prefer to be…

( )	( )	( )	( )	( )	( )	( )
-3	-2	-1	0	+1	+2	+3
Much cooler	Cooler	Slightly cooler	Without change	Slightly warmer	Warmer	Much Warmer

Figure 4 – Survey questionnaires – thermal perception questions

Upon their arrival, respondents were asked to take a couple of minutes to settle in and experience the thermal environment. During that time, the experiment was explained briefly. The subjects then received the first part of the questionnaire on thermal perception and were left alone in the room. Subjects were allowed to read, study, or chat on the phone, but were requested to remain seated at all times and not greatly alter the position of the chair. About 25 minutes later, subjects filled out the second part of the questionnaire. They were then led to the other room, where they were asked to fill out the third part of the questionnaire after a brief period of exposure. The starting room could be either the AC room or the roof pond room, in a random order. Each participant thus cast three votes, evaluating both thermal environments in sequence.

2.5. Thermal control

Thermal conditions in the air-conditioned room were checked before subjects arrived in order to ensure similar conditions to the roof pond room in terms of indoor air temperature. Since there was little control over thermal conditions in the room with the roof pond, the set-point temperature of the AC unit in the second test room was adjusted so that both rooms had the same indoor air temperature.

2.6. PMV calculation

According to ISO 7726, the mean radiant temperature ($\mathbf{T_{MRT}}$) can be estimated with acceptable accuracy from the globe temperature and a coincident airspeed measurement, as follows (for forced convection):

$$T_{MRT} = \left[\left(T_g + 273.15\right)^4 + \frac{1.1\times10^8 v_a^{0.6}}{\varepsilon D^{0.4}} \times \left(T_g - T_a\right)\right]^{1/4} - 273.15 \qquad \text{(Eq.3)}$$

where:

$\mathbf{T_{MRT}}$ = is the mean radiant temperature, in °C;
$\mathbf{T_g}$ = is the temperature of the globe, in °C;
$\mathbf{v_a}$ = is the air velocity at the level of the globe, in m/s;
$\mathbf{T_a}$ = is the air temperature, in °C;
$\mathbf{D}$ = is the diameter of the globe, in m.

The thermal conditions in the two test rooms, accounting for air temperature and humidity and the mean radiant temperature, were estimated by means of the Predicted Mean Vote (PMV, as in ISO 7730). Calculations were made by the CBE Thermal Comfort online calculation tool (http://comfort.cbe.berkeley.edu/ Hoyt et al., 2017), assuming a metabolic rate of 1 Met and clothing level of 0.3 clo units.

3. Results

3.1. Comparison of roof pond modes

Table 1 shows a comparison of the six tested configurations of the roof pond room in terms of the decrement factor (f) and the Mean Temperature Deviation (MTD).

As the table shows, all decrement factors are lower than 0.1, meaning that the building has a high thermal mass, with indoor air temperature fluctuation about one tenth of the outdoor temperature swing. MTD for the different configurations show more pronounced differences, yet all have positive values (indicating a net heating effect). The shading effect of the roof is responsible for the difference between Configurations 1 and 2, with a drop in MTD; the use of evaporative cooling without movable insulation (Configuration 3) was not as effective as with the insulation when spraying is applied (Configurations 5 and 6). The best performance is obtained for Configuration 6, which combines shading and continuous water spraying, and almost cancels out the environmental heat gains. This configuration was used thereafter to provide chilled water during the thermal comfort sessions.

Table 1: Comparison of given configurations for the roof pond room, averages for the respective monitoring periods

	$(T_{max}$-$T_{min})_{int}$	$(T_{max}$-$T_{min})_{out}$	f	MTD
Configuration 1	1.070	13.059	0.082	0.587
Configuration 2	0.811	14.912	0.054	0.209
Configuration 3	0.660	14.121	0.047	0.367
Configuration 4	0.623	11.655	0.053	0.755
Configuration 5	0.969	12.342	0.079	0.132
Configuration 6	0.797	12.215	0.065	0.064

3.2. Experiment with participants

The administration of comfort questionnaires began on July 26 and ended on September 5 (summer). Participants (n=53, 25 male, 28 female) were on average 33.5 years old and with a Body Mass Index (BMI, calculated as body weight divided by the square of body height, expressed in units of kg/m²) ranging between 18.4-37.2 kg/m², thus varying from 'underweight' to 'obese' according to WHO categories (WHO, 1995).

Participants came from 15 different countries: Israel (28 participants), USA (5), Brazil (4), India (3), Germany (2), other countries (11). Residency in Israel varied from less than one year (13%) to over 20 years (49%). The majority had just come from non-AC thermal environments (60%), some from an air-conditioned space (34%) and a few from public transport/car (air-conditioned).

3.3. Air temperature during exposure

Measured air temperature during the various sessions was near the upper threshold for adaptive comfort during that period, with minor differences between the two rooms (Figure 5). The adaptive comfort range was for 80% acceptability (± 4.5ºC above/below the adaptive comfort temperature of 23.4°C, as obtained for the local mean for the period according to new developments of the adaptive comfort approach for residential buildings – Kim et al., 2016).

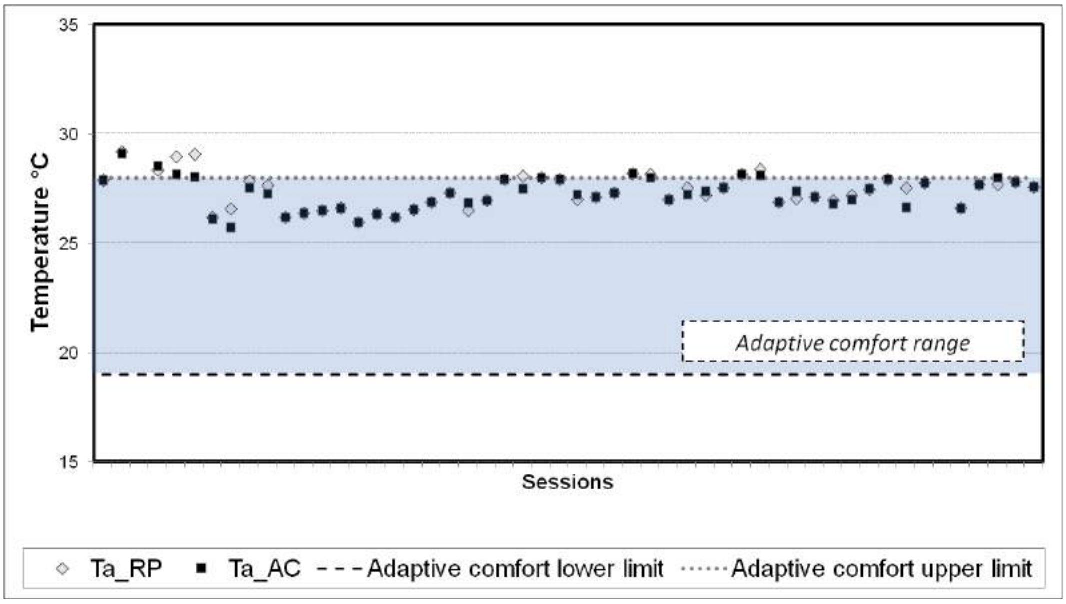


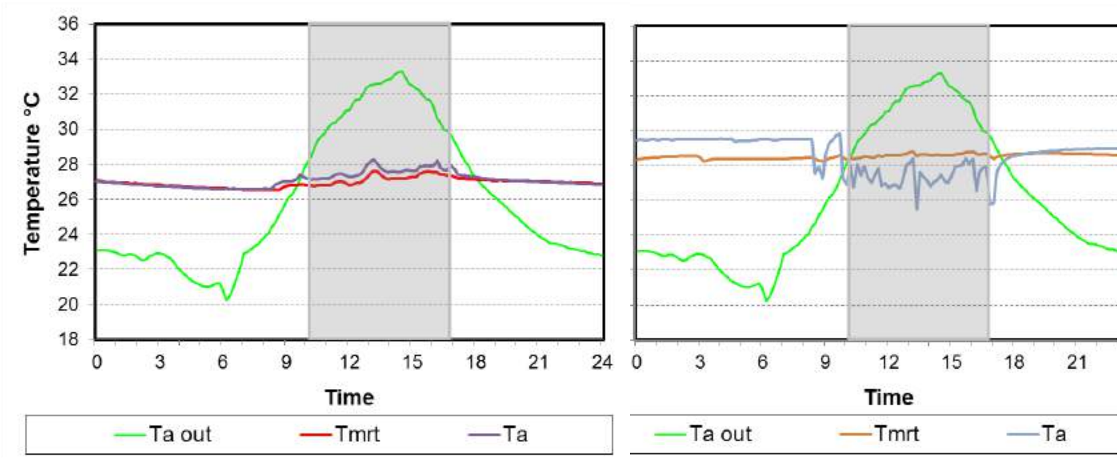
Figure 5 – Air temperature conditions in both rooms during the 53 sessions

One-way ANOVA tests for the measured data showed no statistically significant difference ($p>0.05$) between rooms in terms of air temperature, with nearly equal variances (Table 2). During the change from one room to another, indoor air conditions were almost uniform, with very subtle changes, yet without statistical significance.

Table 2: One-way ANOVA results between the two rooms for Ta data

Group	Mean	Variance	F	p-value	F critical
Roof Pond (RP)	27.38	0.598004			
AC room	27.29	0.526353	0.358607	0.550663	3.938111

Figure 6 shows air and mean radiant temperature during sessions in both rooms on a typical day (August 21). During the sessions (shaded rectangle in the graph), although indoor temperatures were quite similar, surface temperatures presented opposite behavior: in the air-conditioned room, surface temperatures were above indoor air temperature, whereas in the roof pond room the reverse occurred. The average difference of measured surface temperatures in the air-conditioned room during sessions showed a mean increase of 1.4 K, while in roof pond surface temperatures closely followed air temperatures (mean drop -0.2 K).



a) b)

Figure 6 – Mean radiant temperature (T_{MRT}), air temperature indoors (Ta) and outdoors (Ta_out): a) in the roof pond room (left) and b) in the AC room (right) on August 21. The highlighted area corresponds to the period of session

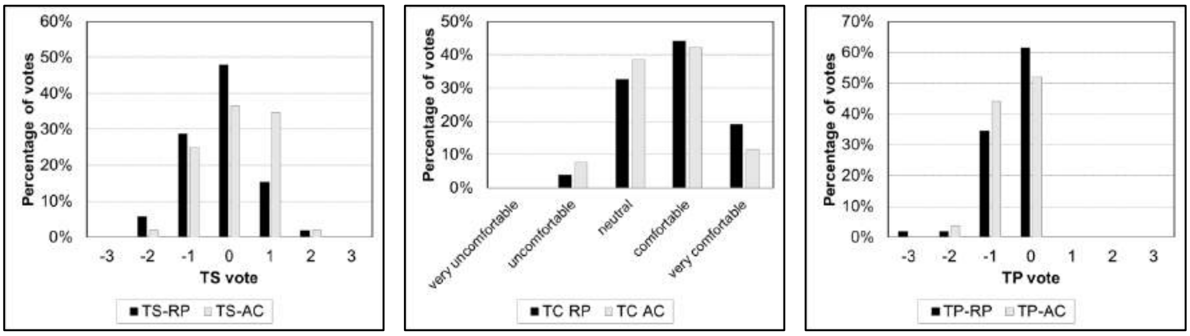
3.4. PMV compared with reported thermal sensation

Since air temperature in both rooms was similar, but the roof pond room had a lower $\mathbf{T_{MRT}}$, conditions in this room were expected to be slightly cooler. This was in fact the case: the roof pond room was cooler on average by 0.36 units on the PMV scale (Table 3).

Table 3: Calculated PMV and reported thermal sensation in the two rooms

PMV			Thermal Sensation		
AC room	RP room	diff	AC room	RP room	diff
0,25	-0,12	0,36	0,27	-0,22	0,49

The subjective thermal sensation reflected the PMV scores – but as Table 3 shows, the effect was magnified: The RP room was considered slightly cooler than predicted by the PMV. For the three aspects analyzed (TS, TC and TP), results show a slight difference in percent rates for each category of the scales, with the roof pond room having most comfortable thermal conditions, as felt by participants (Figure 7). Almost half of TS votes in the roof pond room correspond to TS=0 ("neutral"), whereas more than half of the sample prefers that room to be without change ("neither warmer nor cooler"). Comfort assessment indicated that both rooms are predominantly felt as comfortable/very comfortable, whereas the roof pond room has slightly more votes in these two categories (63% vs. 54% in the air-conditioned room). However, differences in comfort were minor: means differed only slightly between both rooms by a tenth of assessment vote and medians were the same, without statistical significance. The same applies to TS and TP votes, which also had equal medians. Mean values for TS showed a drop of three tenths of TS vote in the roof pond room and a corresponding positive rise of one tenth of a TP vote, though without statistical significance. TS votes in this case almost reached statistical significance (p=0.07) (Table 4).



a) b) c)

Figure 7 – TS, TC and TP votes in the roof pond (RP) and air-conditioned (AC) room

Table 4: One-way ANOVA results between the two rooms for TS, TC and TP

Group	Mean	Median	Variance	F	p-value	F critical
TS (roof pond)	-0.21	0	0.71908			
TS (AC room)	0.10	0	0.755279	3.33913	0.070574	3.934253
TC (roof pond)	2.79	3	0.640649			
TC (AC room)	2.58	3	0.641026	1.815534	0.180831	3.934253
TP (roof pond)	-0.44	0	0.408371			
TP (AC room)	-0.52	0	0.332956	0.415056	0.520861	3.934253

One-way ANOVA for votes cast during the time spent in the first room showed a change between the first TS vote at time stamp 1 and that of time stamp 2 (Table 5). In both rooms, such "adjustment" over time of TS was statistically significant (p<0.05 in the roof pond room, p<0.01 in the air-conditioned room) and meant a drop of approximately 0.7 TS vote in both rooms from the time subjects entered the first room (time stamp 1) to the time they left, about 25-30 minutes later (time stamp 2). Note that changes in indoor Ta conditions during the two first two time stamps were negligible, irrespective of the room.

Comparisons between rooms were obtained from the transition from time stamp 2 to time stamp 3, which involved the change of rooms (Tables 6, 7). During that transition, air temperature in both rooms remained almost unchanged, with statistically insignificant and negligible differences (p>0.01). However, subjective thermal sensation votes showed larger variations: a rise of 0.6 TS vote when moving from the roof pond room to the air-conditioned room (p=0.01) and a drop of 0.3 TS vote when going in the opposite direction. Changes in TP had no statistical significance and were subtler, but corroborated TS votes, with a small drop of 0.1 TP vote when coming from roof pond to AC, meaning a very slight preference for cooler conditions, and with a small rise of 0.3 TP vote when coming from AC to roof pond.

Table 5: One-way ANOVA results between the two rooms for two time stamps and for TS

Group	Mean	Variance	F	p-value	F critical
Time stamp 1 (roof pond)	0.50	1.14000			
Time stamp 2 (roof pond)	-0.15	0.85538	5.570547	0.022208	4.03431
Time stamp 1 (AC)	0.76	1.02333			
Time stamp 2 (AC)	0.08	0.57667	7.225	0.009852	4.042652

Table 6: One-way ANOVA results between the two rooms for two time stamps and for TS

Group	Mean	Median	Variance	F	p-value	F critical
Time stamp 2 (AC room)	0.08	0	0.576667			
Time stamp 3 (roof pond)	-0.24	0	0.690000	2.021053	0.161597	4.042652
Time stamp 2 (roof pond)	-0.15	0	0.855385			
Time stamp 3 (AC room)	0.46	1	0.658462	6.504065	0.013873	4.03431

Table 7: One-way ANOVA results between the two rooms for two time stamps and for TP

Group	Mean	Median	Variance	F	p-value	F critical
Time stamp 2 (AC room)	-0.63	-1	0.592391			
Time stamp 3 (roof pond)	-0.33	0	0.318841	2.240557	0.141263	4.051749
Time stamp 2 (roof pond)	-0.63	-1	0.549858			
Time stamp 3 (AC room)	-0.78	-1	0.333333	0.670968	0.416453	4.026631

4. Conclusions

Occupants exposed to indoor thermal conditions in two test rooms with similar air temperature conditions reported small but in statistically significant differences in terms of their thermal assessment (TS, TC and TP). A room equipped with radiant cooling panels was perceived as less warm and as providing more comfortable conditions than a similar room equipped with a split AC unit cooled to the same air temperature. The difference in TS votes was somewhat greater than the difference in PMV calculated for the rooms.

The slightly inferior performance of the AC room resulted from the reduced effect of air conditioning on the room's surface temperatures as the AC unit was only operated during a given session. Measurements of the surface temperatures indicated that structural cooling and thermal stabilization is obtained in the roof pond room by radiant cooling, whereas in the AC room thermal control is achieved only within the short period of the session through sudden changes in the air temperature. Since the use of air-conditioning systems normally occurs only when a given indoor environment is in use, the roof pond room proves to be able to provide possibilities of use without user's interference.

As in the reported studies in the introductory section of this paper, particularly in Meggers et al. (2017), participants were able to perceive a superior performance of the passive environment despite negligible differences in air temperature in the rooms evaluated and relatively small differences in Tmrt.

5. Acknowledgements

Meteorological data were kindly supplied by David Klepatch, Head-technician of Ben-Gurion University Meteorological Station. The second author's stay in Israel was supported by a scholarship from The Brazilian Funding Agency CAPES.

6. References

ASHRAE (2012). Chapter 6: Panel heating and cooling. ASHRAE Handbook: HVAC Systems and Equipment. Altanta, GA, American Society of Heating, Refrigerating and Air Conditioning Engineers Inc.

Babiak J, Olesen BW, Petras D. (2009). Low temperature heating and high temperature cooling: Embedded water based surface heating and cooling systems. Rehva.

Bitan A, Rubin S. (1991). Climatic Atlas of Israel for Physical Planning and Design, Israel Meteorological Service and Ministry of Energy and Infrastructure.

Erell E, Etzion Y, Brunold S, Rommel M, Wittwer V. (1992). A passive cooling laboratory building for hot-arid zones. Proceedings of the 3rd International Conference - Energy and Building in Mediterranean Area, Thessaloniki, Greece, April 8-10, 1992, pp. 117-124.

Erell E, Etzion Y. (1999). Analysis and experimental verification of an improved cooling radiator. Renewable Energy, 16(1-4), 700-703.

Hoyt T, Schiavon S, Piccioli A, Cheung T, Moon D, Steinfeld K. (2017). CBE Thermal Comfort Tool. Center for the Built Environment, University of California Berkeley, http://comfort.cbe.berkeley.edu/

Imanari T, Omori T, Bogaki K. (1999). Thermal comfort and energy consumption of the radiant ceiling panel system.: Comparison with the conventional all-air system. Energy and buildings, 30(2), 167-175.

ISO 10551. Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales. (1995). International Organization for Standardization, Geneva.

ISO 7726. Ergonomics of the thermal environment — Instruments for measuring physical quantities. (1998). International Organization for Standardization, Geneva.

Karmann C, Schiavon S, Bauman, F. (2017). Thermal comfort in buildings using radiant vs. all-air systems: A critical literature review. Building and Environment, 111, 123-131.

Kim J, De Dear R, Parkinson T, Candido C, Cooper P, Ma Z, Saman W. (2016). Field study of air conditioning and thermal comfort in residential buildings. Proceedings of the 9th Windsor Conference: Making Comfort Relevant. Windsor, UK. London: NCEUB, April 7-10, 2016.

Li R, Yoshidomi T, Ooka R, Olesen BW. (2015). Field evaluation of performance of radiant heating/cooling ceiling panel system. Energy and Buildings, 86, 58-65.

Meggers F et al. (2017). The Thermoheliodome-Air conditioning without conditioning the air using radiant cooling and indirect evaporation. Energy and Buildings, 157, 11-19.

Miriel J, Serres L, Trombe A. (2002). Radiant ceiling panel heating–cooling systems: experimental and simulated study of the performances, thermal comfort and energy consumptions. Applied Thermal Engineering, 22(16), 1861-1873.

Mustakallio P, Bolashikov Z, Rezgals L, Lipczynska A, Melikov A, Kosonen R. (2017). Thermal environment in a simulated double office room with convective and radiant cooling systems. Building and Environment, 123, 88-100.

Schellen L et al. (2011). The influence of local effects on thermal sensation under non-uniform environmental conditions: gender differences in thermophysiology, thermal comfort and productivity during convective and radiant cooling. Physiology and Behaviour, 107(2), 252-261.

Schellen L et al. (2013). Effects of different cooling principles on thermal sensation and physiological responses. Energy and Buildings, 62, 116-125.

Sharifi A, Yamagata Y. (2015). Roof ponds as passive heating and cooling systems: A systematic review. Applied Energy, v. 160, p. 336–357.

World Health Organization - WHO (1995). Physical status: the use and interpretation of anthropometry. Report of a WHO Expert Committee. WHO Technical Report Series 854. World Health Organisation, Geneva.

Reliability of characterising buildings as *HVAC* or *NV* for making assumptions and estimations in case studies

Rick Kramer[1] , Henk Schellen[2] , Jos van Schijndel[2], Wim Zeiler[1]

[1] Building Services chair, Department of the Built Environment, Eindhoven University of Technology, the Netherlands, r.p.kramer@tue.nl, w.zeiler@tue.nl;
[2] Building Physics chair, Department of the Built Environment, Eindhoven University of Technology, the Netherlands, h.l.schellen@tue.nl, a.w.m.v.schellen@tue.nl.

Abstract: Buildings are often categorised into HVAC-buildings and naturally ventilated (NV) buildings. This study explores the extent to which a fully air-conditioned museum adheres to the typology of being an HVAC-building regarding (i) the acceptable indoor temperature range and variation, (ii) the clothing variation, (iii) the validity of the PMV model. Estimations of these aspects and of the PMV model's inputs are based on data from the literature that differentiates between HVAC and NV buildings. Then, the estimated aspects are compared with experimental data based on a large-scale measurement and survey study (n=1250) at the Hermitage Amsterdam museum. Conclusions: (i) More seasonal temperature variation is accepted in the museum than expected for an HVAC-building; (ii) The permissible temperature range exactly matches that of HVAC-buildings, i.e. neutral ±1.2°C; (iii) Clothing behaviour in the museum corresponds to NV-buildings; (iv) Metabolic rate was found to be 22% higher than estimated; (vi) PMV model increasingly underestimates mean thermal sensation towards cold and warm sides of thermal spectrum; (vii) Outdoor temperature significantly influences thermal sensation indoors. Hence, categorising a building solely based on the criteria of perceived control into HVAC-building or NV-building yields unreliable estimations of clothing behaviour, acceptable temperature range, and validity of the PMV-model.

Keywords: characterisation, comfort, adaptive, clothing, PMV

1. Introduction

From the beginning of the 1990's a clear distinction has evolved between HVAC-buildings and NV-buildings regarding comfort, e.g. (Bush 1992). In HVAC-buildings, people mostly rely on behavioural adaptation, e.g. change of clothes, while people in NV-buildings also employ psychological adaptation, e.g. expectations (Fountain et al. 1996), and physiological adaptation, e.g. acclimatization (de Dear et al. 2013). For NV-buildings, several Adaptive Temperature Limits (ATL) standards have been developed, intrinsically including the effect of psychological adaptation and physiological adaptation (CEN 2007; ANSI/ASHRAE 2013). These have been criticized (Halawa & van Hoof 2012; van Hoof & Hensen 2007), updated (Humphreys et al. 2013) and extended to specific countries (van der Linden et al. 2006).

There is a clear distinction between these buildings regarding the following aspects: (i) clothing variation, e.g. (De Carli et al. 2007), (ii) acceptable indoor temperate ranges, e.g. (Bush 1992; de Dear & Brager 2001), (iii) validity of the PMV model (de Dear & Brager 1998). Hence, it can be helpful to characterise a building as HVAC or NV if estimations of these aspects are needed. However, the validity of characterising one specific building as HVAC or NV to be able to make estimations may be questioned: Important case-specific information may be lost in large databases such as in ASHRAE RP-884 (de Dear & Brager 1998).

This study explores the extent to which a fully air-conditioned museum adheres to the typology of being an HVAC-building regarding (i) the acceptable indoor temperature range and variation, (ii) the clothing variation, (iii) the validity of the PMV model. Estimations of these aspects and of the PMV model's inputs are based on data from the literature that differentiates between HVAC and NV buildings. Then, the estimated aspects are compared with experimental data based on a large-scale measurement and a survey study (n=1250) at the Hermitage Amsterdam museum in the Netherlands.

Section 2 describes the case study museum. Section 3 presents the results of the a priori estimations regarding the inputs of the PMV model for the case study museum, furthermore, the PMV model was used to estimate the predicted acceptable temperature ranges. Section 4 presents the results of the experimentally determined clothing level in the museum, the identified metabolic rate, and the adaptive temperature limits. Section 5 compares the results with results for HVAC and NV buildings from literature. Section 6 provides a discussion and the conclusions.

2. Case study: Hermitage Amsterdam museum

Hermitage Amsterdam (Figure 1) is located in Amsterdam, The Netherlands, and is a sister of The State Hermitage Museum in St. Petersburg, Russia. The museum is housed in a late 17^{th}-century building. Its most recent renovation dates from the years 2007-2009 when the building was transformed into a state-of-the-art museum. Restoring the exterior façade helped to preserve the historical appearance, but all the remaining parts of the building have been rebuilt to accommodate the museum adequately. The building envelope has been upgraded to a high insulation level and particular effort has been spent on making the building envelope airtight.

The building has a symmetrical floor plan: two identical exhibition wings may be recognized by the glass roof on the left and right side in Figure 1a. The exhibition area consists of the main hall (Figure 1b) and adjacent cabinets (Figure 1d). Visitors enter the exhibition area via the stairway from the foyer (Figure 1c).

The museum is opened seven days per week from 10 h until 17 h and has been welcoming 7,000 to 11,000 visitors per week, depending on the exhibition. The experiments have been conducted over a period of one year without a change of exhibition, resulting in a repeatedly weekly visitor profile. On Sunday, Tuesday and Wednesday most visitors have been welcomed, on Monday the least.

An all-air HVAC system was installed to condition the indoor environment. Additionally, floor heating was applied in the non-exhibition areas such as the restaurant and foyer. The employed indoor climate specifications were 21 °C and 50 % RH without permissible fluctuations, aiming for a stable museum environment. As a result, seasonal fluctuations are absent in the current indoor climate. Windows cannot be opened and visitors need to decide on their clothing level prior to starting the museum tour. This implies that visitors have very limited means to improve their individual comfort and have no control over the indoor environment.

The combination of full air-conditioning and no user control had led to the notion that the museum may be characterised as an HVAC building.

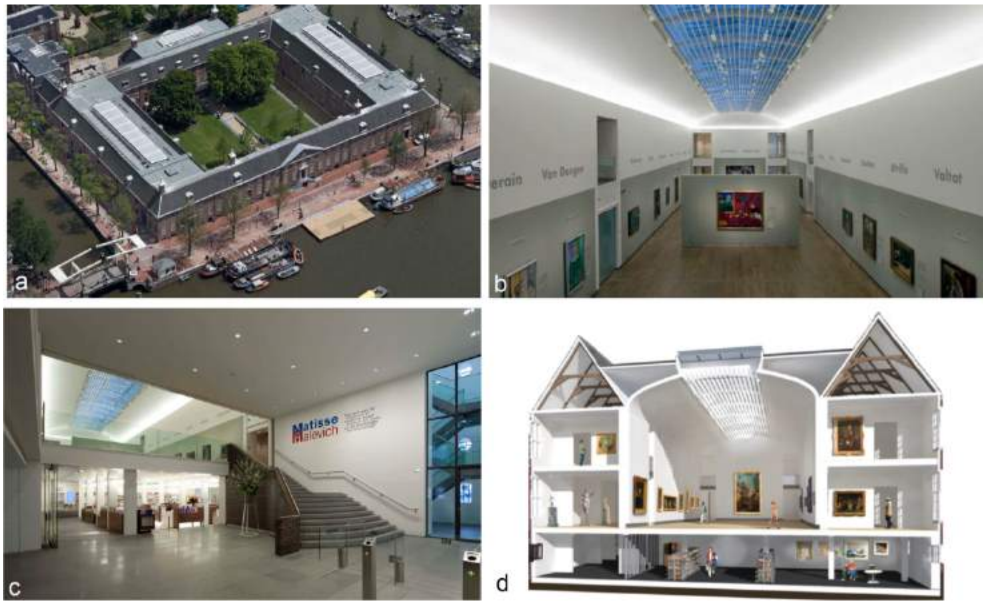


Figure 1. (a) Aerial view of the Hermitage Amsterdam museum (Source: Wooning Aviation). (b) One of two main exhibition rooms with a large glass roof (Source: Luuk Kramer). (c) The entrance stair from the lobby to the main exhibition room with an air curtain to reduce air exchange (Source: Luuk Kramer). (d) A cross-section of one side of the building showing the main exhibition room and adjacent cabinets (Source: Van Heeswijk Architecten).

3. PMV model: a priori estimations

Because ASHRAE RP884 (de Dear & Brager 1998) has demonstrated that the PMV model is valid for HVAC buildings, but not for NV buildings, the PMV model was assumed to be valid for the case study museum 'Hermitage Amsterdam'. In 2015, before the availability of experimental data, the PMV model was used with estimated inputs to determine the acceptable temperature ranges for a museum environment (Kramer et al. 2015). The inputs for the PMV model were estimated, in particular, the clothing behaviour and the metabolic rate.

Table 1 shows the inputs that were used for the PMV model. Relative humidity was kept constant as the relative humidity in the museum environment is often maintained closely to 50%. The metabolic rate was determined from ASHRAE's tabular values (ASHRAE 2013): a time-weighted average of standing relaxed (1.2 met) and walking slowly (2.0 met). The time for standing relaxed (8.5 min) and walking slowly (0.5 min) was determined by observations in the Van Abbe Museum in Eindhoven, the Netherlands.

Table 1. Estimated inputs for the PMV model.

Property	Value	Unit
External work	0	W/m^2
Metabolism	1.24	met
Operative temperature	variable	°C
Relative humidity	50	%
Clothing	f(outdoor temperature metric)	Clo
Air velocity	0.15	m/s

Several relationships are provided in literature for the clothing behaviour as a function of some outdoor reference temperature. In Figure 2, the results of ASHRAE's RP-884 (de Dear & Brager 1998) are compared to the results found by De Carli et al. ((De Carli et al.

2007). The relationships for HVAC buildings are very similar, but the relationships for NV buildings differ significantly. However, a direct comparison is not entirely valid since the reference outdoor temperatures differ, i.e. ‘mean outdoor Effective Temperature’ and ‘outdoor temperature at 6 am’. Nevertheless, the difference between HVAC buildings and NV buildings is evident.

Despite the fact that the museum was characterised as an HVAC building, it was assumed that the clothing behaviour of museum visitors, mostly tourists, is better represented by the relationships for NV buildings: Tourists often combine site-seeing and visiting museums, so, they spend a considerable amount of time outdoors and will be dressed accordingly. The relationship of RP884 for HVAC buildings (de Dear & Brager 1998) was used as input for the PMV model with limits 0.4 and 1.2.

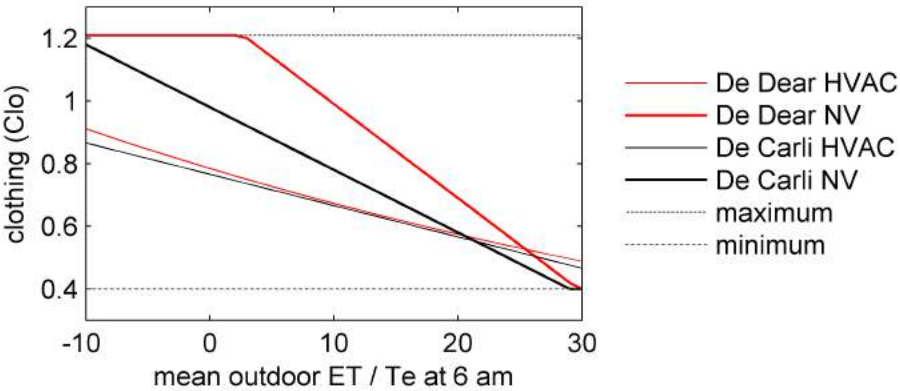


Figure 2. Clo-value as a function of reference outdoor temperature (De Dear et al. 1997; De Carli et al. 2007).

MATLAB 2015a (The Mathworks Inc. 2015) was used to implement the PMV model with the presented inputs and find the indoor temperature limits that result in PMV = -0.5 and PMV = 0.5 (90% acceptance class), and PMV = -0.84 and PMV = 0.84 (80% acceptance class). Figure 3 shows the results. The limits remain constant below an outdoor temperature of 3°C due to the upper limit of the clothing level (1.2 Clo). Furthermore, the indoor temperature range converges towards higher outdoor temperatures.

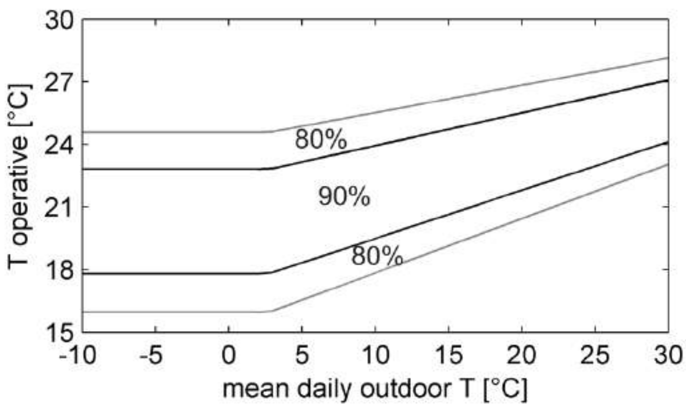


Figure 3. The adaptive limits using the PMV with 90% and 80% acceptance.

4. Experimental data: Hermitage Amsterdam museum

The experimental study at the Hermitage Amsterdam museum was conducted during the period from February 2015 until December 2015. For a detailed description, see (R. P. Kramer et al. 2017). Data acquisition comprised surveys (subjective) and indoor climate measurements (objective). The surveys included nine questions on gender, age, time present in the museum, the acceptability of the thermal indoor environment, thermal sensation, thermal comfort, thermal preference, desire to change the temperature, and clothing level. Indoor measurements consisted of air temperature, radiant temperature, relative air humidity, and airspeed. The indoor operative temperature was used for further analysis, which was calculated as the mean of air temperature and radiant temperature. Outdoor air temperature and relative air humidity were acquired from the museum's weather station via the Building Management System.

During the intervention, the setpoint for relative humidity was maintained at 50 %, and the indoor temperature has been adjusted from 19.5°C to 24°C in such a way that a mean thermal sensation vote (*MTSV*) of approximately 0.5 or -0.5 was to be expected.

Thermal sensation and clothing level were related to a reference outdoor temperature ($T_{\text{e,ref}}$) that was calculated according to:

$$T_{\text{e,ref}} = \frac{T_{\text{e,i}} + 0.8T_{\text{e,i}-1} + 0.4T_{\text{e,i}-2} + 0.2T_{\text{e,i}-3}}{2.4} \quad (1)$$

where $T_{\text{e,i}}$ is the average outdoor temperature of the survey day, $T_{\text{e,i-1}}$ the average of the day before, etc. The average is the arithmetic mean of the minimum and maximum outdoor temperature of the given day (van der Linden et al. 2006). It is an implementation of the exponentially weighted running mean outdoor temperature by (Nicol & Humphreys 2002).

Every survey day resulted in an *MTSV*, which is the average of all Thermal Sensation Votes (*TSV*) of that day. The following *MTSV*s were used for constructing the temperature limits: -0.1 < *MTSV* < 0.1 to represent the neutral temperature, -0.6 < *MTSV* < -0.4 for the lower limit and 0.4 < *MTSV* < 0.6 for the upper limit. The range between the lower and upper limit is considered as the 90 % acceptance class (Fanger 1970). To determine the neutral temperature as a function of $T_{\text{e,ref}}$, the operative indoor temperatures of the survey days that yielded an *MTSV* between -0.1 and 0.1 were plotted as a function of $T_{\text{e,ref}}$. Subsequently, univariate linear least squares regression was applied to find the linear relation between these neutral temperatures and $T_{\text{e,ref}}$. This procedure was repeated to find the linear relation of the upper and lower temperature limits as a function of $T_{\text{e,ref}}$.

Figure 4 shows the results. The text labels show the *MTSV* of the survey days. The *MTSV*s show a strong linear relation with $T_{\text{e,ref}}$ for the upper temperature limit (R^2 = 0.97, $P < 0.05$), the neutral temperature (R^2 = 0.84, $P < 0.1$), and lower temperature limit (R^2 = 0.95, $P < 0.1$). The solid lines represent the linear regressions. However, it must be noted that the data points for the upper limit were limited, whereas the neutral and lower limit are fitted to considerably more data points. The neutral temperatures are calculated according to,

$$T_{neutral} = 19.5 + 0.175\, T_{\text{e,ref}} \quad (2)$$

Because the regressions did result in nearly parallel limits, the final limits resulted from plotting the lower and upper temperature limits at exactly -1.2 °C and +1.2 °C from the neutral temperatures (dotted lines). Hence, the upper temperature limit is calculated according to,

$$T_{upper\ limit} = 20.7 + 0.175\ T_{\mathrm{e,ref}} \tag{3}$$

and the lower temperature limit is calculated according to,

$$T_{lower\ limit} = 18.3 + 0.175\ T_{\mathrm{e,ref}} \tag{4}$$

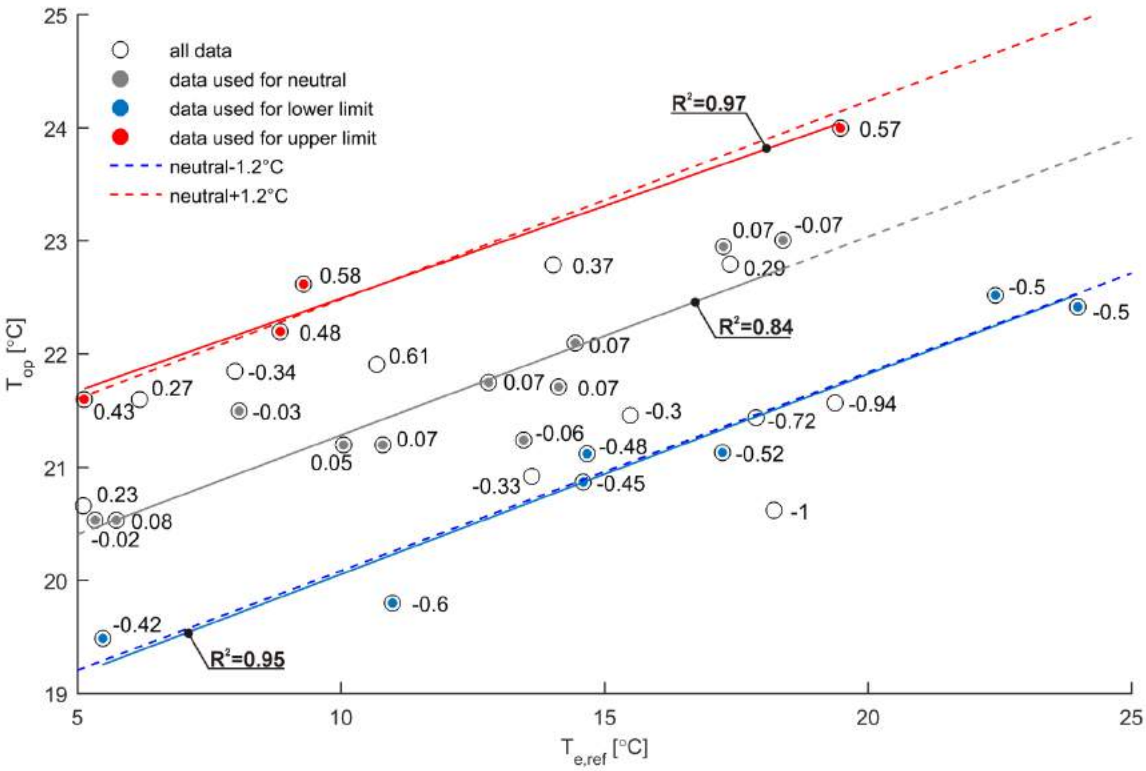


Figure 4. Construction of adaptive temperature limits for the museum environment (Hermitage Amsterdam) (R. P. Kramer et al. 2017).

Clothing level was determined based on the participants' survey responses. The transcription to Clo-value was based on numerical values provided by ASHRAE (ASHRAE 2013). Figure 5 shows the *Clo*-value related to $T_{\mathrm{e,ref}}$. The clothing level strongly depends on the outdoor reference temperature, with mean clothing levels ranging from 0.9 in winter to 0.4 in summer. The clothing level did not significantly differ between men and women (P > 0.05). Linear regression was applied on the mean *Clo*-values in relation to $T_{\mathrm{e,ref}}$ of each survey day (R^2 = 0.69) resulting in *Clo* = 0.91 – 0.018 $T_{\mathrm{e,ref}}$. Clothing differences among individual respondents were very large: some individuals practically wore summer outfits in winter, and others wore winter outfits towards summer.

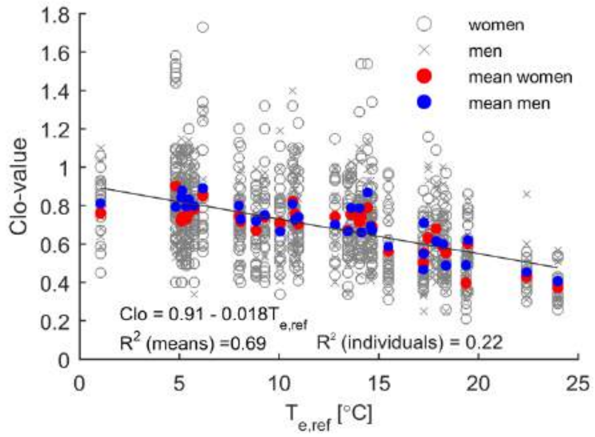


Figure 5. Clothing level as a function of the reference outdoor temperature. Data of individual visitors and the means of men and women are presented.

5. Comparing the a priori estimations with experimental data and literature

The results from the a priori estimations and the experimental case study at the Hermitage Amsterdam museum can now be compared with each other and with results from the literature.

Figure 6 compares the following adaptive temperature limits: (i) the estimated limits for the museum using the PMV model; (ii) the limits found by experiments at the case study museum; (iii) the limit for HVAC buildings according to the ASHRAE RP884; (iv) the limits for NV buildings stipulated by ASHRAE Standard 55. The results show that the limits found by experiments at the museum are characterised by the same temperature range as the temperature range for HVAC buildings, i.e. neutral ±1.2°C. However, the slope, i.e. the correlation between the acceptable indoor temperature and the reference outdoor temperature, is larger than that for HVAC buildings. In fact, the slope of the temperature limits is pretty close to the average of the slopes of HVAC and NV buildings. The a priori estimation by the PMV model was correct regarding this slope, but was significantly off regarding the acceptable temperature range.

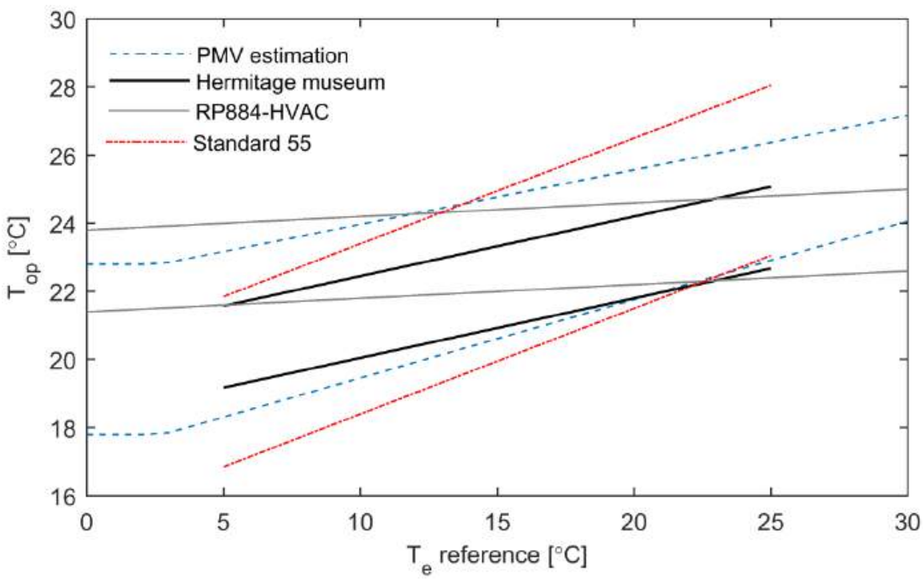


Figure 6. Adaptive temperature limits according to various sources: estimated using the PMV model; experimental study at the Hermitage Amsterdam museum; ASHRAE RP884 (HVAC buildings); ASHRAE Standard 55 (NV buildings).

Figure 7 compares the relationships between the clothing level and the reference outdoor temperature. The difference in clothing level between HVAC buildings and NV buildings is much larger according to ASHRAE RP884 compared to the results found by De Carli et al. The assumption that the clothing behaviour in the case study museum is much more in line with the clothing behaviour as found in NV buildings than in HVAC buildings, seems to be correct. However, the a priori estimation of the clothing behaviour according to the RP884 NV buildings relationship appears to be inaccurate as the actual clothing behaviour is much closer to the clothing relationship as found by De Carli et al for NV buildings.

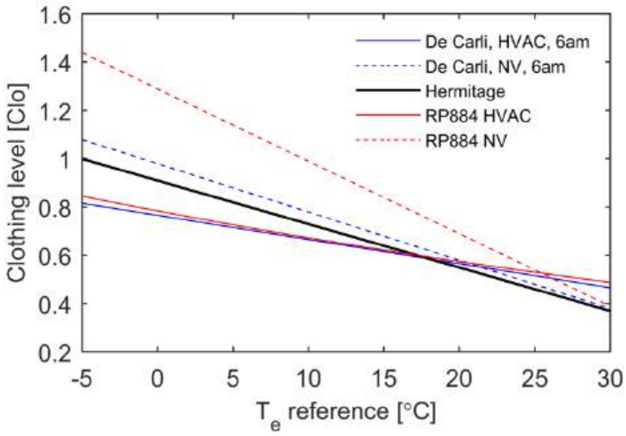


Figure 7. Clothing level as a function of reference outdoor temperature according to De Carli et al. (De Carli et al. 2007), ASHRAE RP884 (de Dear & Brager 1998), and experimental data from the Hermitage Amsterdam museum (R. P. Kramer et al. 2017).

Figure 8 compares the a priori estimated metabolic rate with the identified metabolic rate from experimental data using the PMV model. See (R. Kramer et al. 2017) for a detailed description of the methodology. Here, only a brief description will follow: for each respondent, the metabolic rate was identified using the PMV model. All inputs were known from the survey data and indoor climate measurements, except the metabolic rate. The metabolic rate was optimized in such a way that the PMV was equal to the respondents' TSV. By repeating this procedure for all 1250 respondents, the distribution was obtained as depicted in Figure 8. The median metabolic rate was determined to be 1.51 met, which is 22% higher than the a priori estimated metabolic rate which was 1.24 met. So, despite the time-weighting average, the metabolic rate was significantly underestimated.

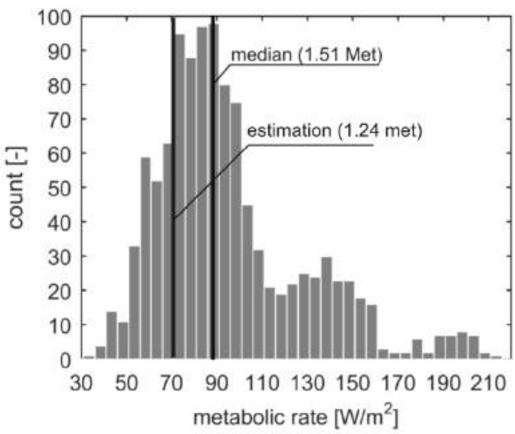


Figure 8. Comparing the a priori estimated metabolic rate with the metabolic rate identified from experimental data (R. Kramer et al. 2017).

Figure 9 shows the prediction accuracy of the PMV model for the case study museum if all inputs are determined as accurately as possible, i.e.: indoor air temperature, radiant temperature, airspeed, and air humidity were used from climate measurements; clothing behaviour and thermal sensation votes were used from survey data. The metabolic rate was determined to be 1.51 met, see Figure 8. Even if the inputs match the actual situation in the case study museum and further data are used from respondents themselves, the PMV model cannot be regarded as valid for this case study building which is a priori considered to be a typical 'HVAC-building'. The PMV model underestimates the museum visitors' sensation increasingly towards the extremities, i.e. warm and cold sides of the spectrum.

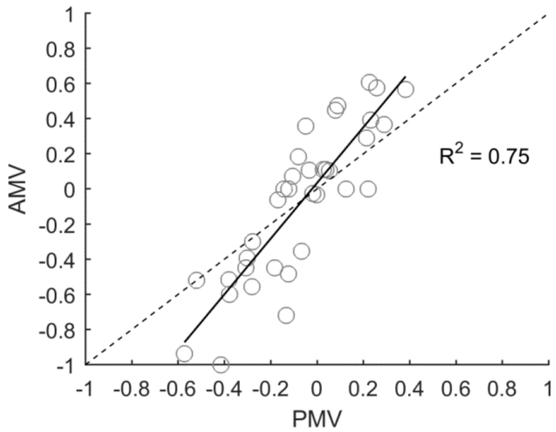


Figure 9. Actual Mean Votes (AMV) vs Predicted Mean Votes (PMV). The PMV model was used with all inputs determined from measurements and surveys, except the metabolic rate, which was identified at 1.51 met (R. Kramer et al. 2017).

6. Discussion and conclusions

From the 1990's, a clear distinction has evolved between HVAC buildings, in which the user perceives very limited control over the thermal environment, and NV buildings, in which the user perceives a substantial level of control. A few aspects differ significantly between these buildings: Clothing is more varied over a year in NV buildings than in HVAC buildings, the acceptable indoor temperature variation over a year is larger in NV buildings than in HVAC buildings, and some studies have found the PMV model to be valid for HVAC buildings whereas it is considered to be invalid for NV buildings. This has raised the question if reliable estimations and assumptions can be made by categorising a building as HVAC or NV. For a case museum in the Netherlands, the Hermitage Amsterdam, a priori estimations have been made of the metabolic rate (1.24 met), the clothing behaviour (based on literature), and adaptive temperature limits were estimated using the PMV model. Then, an experimental case study at the Hermitage Amsterdam museum has yielded indoor climate data, outdoor climate data, and subjective data of 1250 respondents regarding clothing behaviour and thermal sensation.

The data allowed to identify the median metabolic rate of the visitors population by tuning the PMV model. The identified metabolic rate (1.51 met) was found to be 22% higher than the a priori estimated metabolic rate (1.24 met). Furthermore, although the assumption that visitors' clothing behaviour is more in line with NV buildings appears to be correct, the assumed relationship between clothing level and outdoor temperature turns out to be inaccurate. However, these inaccuracies can only partly explain the deviation between the estimated temperature limits and the experimentally derived limits: Even if the

PMV model's inputs are based on accurate experimental data, it increasingly underestimates the thermal sensation of the museum visitors towards the cold and warm sides of the spectrum. Furthermore, although the museum visitors were to be expected to accept a wider temperature range than predicted by the PMV model, the contrary appears to be true: the acceptable temperature range is stringent and exactly equal, i.e. neutral ±1.2°C, to that of HVAC-type office buildings according to ASHRAE RP884. Hence, although the museum is considered as an HVAC building, the validity of the PMV model appears to be limited.

In conclusion, categorising a building based on the criteria of perceived control into HVAC-building or NV-building forms an unreliable basis for estimations on clothing behaviour and acceptable indoor temperature range, at least for this case study museum.

The results and conclusions raise the question as to whether there should be separate categories and calculations for special environments such as museums: People enter wearing clothes often more attuned to the outdoor climate conditions and people tend to walk around more in a museum than in an office environment resulting in a higher metabolic rate. The same question may apply to other special environments such as shops. Note that both in museums and shops, staff and visitors dress differently. Hence, improving visitors' comfort may imply attuning staff's clothing ensembles.

7. References

ANSI/ASHRAE, 2013. Standard 55: Thermal environmental comfort conditions for human occupancy.

ASHRAE, 2013. Thermal Comfort. In M. S. Owen, ed. *ASHRAE Handbook of Fundamentals*. Atlanta: Comstock, W. Stephen, p. 9.1-9.30.

Bush, J.F., 1992. A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand. *Energy and Buildings*, 18, pp.235–249.

De Carli, M. et al., 2007. People's clothing behaviour according to external weather and indoor environment. *Building and Environment*, 42(12), pp.3965–3973. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132306003672 [Accessed November 25, 2014].

CEN, 2007. *EN-15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*, Brussels: European Committee for Standardization.

de Dear, R. et al., 2013. Progress in thermal comfort research over the last twenty years. *Indoor air*, 23, pp.442–461. Available at: http://www.ncbi.nlm.nih.gov/pubmed/23590514 [Accessed November 20, 2013].

De Dear, R., Brager, G. & Cooper, D., 1997. *ASHRAE RP-884: Developing an Adaptive Model of Thermal Comfort and Preference*, Atlanta.

de Dear, R.J. & Brager, G.S., 1998. Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions*, 104, pp.145–167.

de Dear, R.J. & Brager, G.S., 2001. The adaptive model of thermal comfort and energy conservation in the built environment. *International Journal of Biometeorology*, 45(2), pp.100–108.

Fanger, O., 1970. *Thermal Comfort: analysis and applications to environmental engineering.*, Copenhagen: Danish Technical University Press.

Fountain, M., Brager, G. & de Dear, R., 1996. Expectations of indoor climate control. *Energy and Buildings*, 24(3), pp.179–182. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778896009887.

Halawa, E. & van Hoof, J., 2012. The adaptive approach to thermal comfort: A critical overview. *Energy and Buildings*, 51, pp.101–110. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778812002241 [Accessed September 26, 2013].

van Hoof, J. & Hensen, J.L.M., 2007. Quantifying the relevance of adaptive thermal comfort models in moderate thermal climate zones. *Building and Environment*, 42(1), pp.156–170. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132305003550 [Accessed September 18, 2013].

Humphreys, M. a., Rijal, H.B. & Nicol, J.F., 2013. Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. *Building and Environment*, 63, pp.40–55. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132313000474 [Accessed August 14, 2013].

Kramer, R. et al., 2017. Improving rational thermal comfort prediction by using subpopulation characteristics: a case study at Hermitage Amsterdam. *Temperature*, p.0. Available at: http://dx.doi.org/10.1080/23328940.2017.1301851.

Kramer, R.P., Schellen, H.L. & Schijndel, J.W.M. Van, 2015. Towards temperature limits for museums : a building simulation study for four museum zones with different quality of envelopes. In M. Loomans & M. te Kulve, eds. *Healthy Buildings Europe*. Eindhoven: Eindhoven University Press, pp. 1–8.

Kramer, R.P., Schellen, L. & Schellen, H.L., 2017. Adaptive temperature limits for air-conditioned museums in temperate climates. *Building Research & Information*, pp.1–12.

van der Linden, A.C. et al., 2006. Adaptive temperature limits: A new guideline in The Netherlands. *Energy and Buildings*, 38(1), pp.8–17.

Nicol, J.F. & Humphreys, M.A., 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, 34(6), pp.563–572.

The Mathworks Inc., 2015. MATLAB.

Dynamic Evaluation Method for Indoor Thermal Environmental Acceptability Using P-R Chart

Masanari Ukai[1] and Tatsuo Nobe[2]

[1] Kogakuin University, Tokyo, Japan, ukai_masanari_0302@yahoo.co.jp
[2] Kogakuin University, Tokyo, Japan, nobe@cc.kogakuin.ac.jp

Abstract: This study was conducted to characterise thermal environmental acceptability for various air-conditioning systems. The authors developed a new thermal comfort index called a P-R chart using the concepts of "provided temperature" and "required temperature" for use in evaluating uniform, high-quality indoor thermal environments and non-uniform, unsteady thermal environments. In this study, first, the authors surveyed the required temperature distribution of workers. Then they surveyed indoor thermal environmental stabilities in the four offices during the summer with different air-conditioning systems to calculate provided temperature distribution. Finally, the indoor thermal acceptability in offices was evaluated using the P-R chart. The results showed that the convective air-conditioning systems caused wide temporal and spatial variations in the thermal environment. Therefore, in buildings with convective air-conditioning systems, even if the planar average thermal environment is categorised as comfortable, it is presumed that workers sensitive to cold or heat will complain of discomfort more frequently than those in buildings with radiant air-conditioning systems and floor-supply displacement HVAC systems, because the probability of workers sitting in cold- or hot-spot areas is higher in the former case.

Keywords: Thermal acceptability, Thermal comfort, Provided temperature, Required temperature, P-R chart

1. Introduction

The evaluation of thermal comfort based on conventional indices involves consideration of a single person in a room as being representative of a group of people with common characteristics. Therefore, conventional air-conditioning systems endeavour to provide comfortable and thermally uniform environments by preventing temporal and spatial variations in the thermal environment. However, conventional convective air-conditioning systems may create air drafts and nonuniform thermal environments, resulting in discomfort. In contrast, radiant cooling systems are expected to improve thermal comfort because they do not create potentially uncomfortable air drafts. In a survey of thermal environment acceptability conducted by the authors, workers sensitive to cold frequently expressed discomfort in offices with convective air-conditioning systems. In contrast, offices with radiant cooling systems produced fewer complaints from sensitive workers (Ukai et al, 2014). However, no method of evaluating temporal and spatial variations in the thermal environment has been established yet. Therefore, differences in the thermal comfort of each air-conditioning system (e.g. convective air-conditioning systems, radiant air-conditioning systems) are evaluated from a subjective perspective of the workers. Moreover, in a survey of thermal environment acceptability in offices conducted by the authors, votes indicating an unacceptably hot environment concentrated soon after workers started sitting. Conversely, votes indicating an unacceptably cold environment occurred in greater numbers when the workers had been sitting for a long time (Ukai et al, 2014).

It is assumed that the indoor thermal environmental acceptability is caused by differences in the comfortable temperature of each worker attributable to changes in metabolic rate and choice of clothing in addition to indoor thermal environment evenness. The authors developed a new thermal comfort index called the P-R chart using the concepts of "provided temperature" and "required temperature" for use in evaluating uniform, high-quality indoor thermal environments and non-uniform, unsteady thermal environments (Ukai et al, 2016). Provided temperature is a quantitative index of the indoor thermal environment, defined as the temperature of a hypothetical uniform thermal environment equivalent to the real environment. Required temperature is defined as the provided temperature at which a person in the room perceives a neutral thermal sensation. This study was conducted to characterise thermal environmental acceptability for various air-conditioning systems. First, the authors surveyed the required temperature distribution of the workers. Then the authors surveyed indoor thermal environmental stabilities in four offices during summer with different air-conditioning systems to calculate provided temperature distribution. Finally, the authors evaluated the indoor thermal acceptability in offices using the P-R chart.

2. Concept of evaluating thermal environmental acceptability using P-R chart

2.1. Provided temperature

Provided temperature is a quantitative index of the indoor thermal environment, defined as the temperature of a hypothetical uniform thermal environment equivalent to the real environment. The conventional index of thermal comfort is derived from air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation. In contrast, provided temperature is derived from four environmental parameters and is intended to reflect the pure indoor physical thermal environment. The authors therefore consider provided temperature to be similar to equivalent temperature. Hence, it is considered that the provided temperature distribution of an evaluated office depends on the type of air-conditioning system present. In this study, the provided temperature was assumed to be the equivalent temperature based on the Madsen method.

2.2. Required temperature

Required temperature is defined as the provided temperature at which a person in the room perceives a neutral thermal sensation. Therefore, required temperature is derived from the metabolic rate and clothing insulation of the person. Hence, the required temperature distribution of an evaluated office is considered to depend on factors, such as the type of business activity occurring, clothing regulations, and gender ratio. In this study, the required temperature was assumed to be the operative temperature at which PMV = 0, based on the metabolic rate and clothing insulation.

2.3. P-R chart

The proposed index employs the provided temperature and required temperature and is hence termed a P–R chart. The values used are all assumed, and conceptual diagrams are shown in Figure 1. This approach applies probabilistic evaluation to thermal acceptability. The thermally neutral line (shown in white on the charts) indicates the points at which the provided temperature and required temperature are equivalent. Therefore, a person whose thermal preference is represented by the white line feels that the thermal environment is acceptable (neither too hot nor too cold). In contrast, the authors considered a case in which 20% of workers preferred a low temperature because their metabolic rate and clothing insulation were high. Assuming that the provided temperature in the indoor thermal environment is 10% skewed to the hot side, in evaluating the indoor thermal environment using this concept, it can be probabilistically determined that 2% of workers feel that the thermal environment is too hot. Moreover, in the case of an indoor thermal environment with a radiant air-conditioning system, the probability of worker complaints decreases because the maldistribution of provided temperature becomes lower.

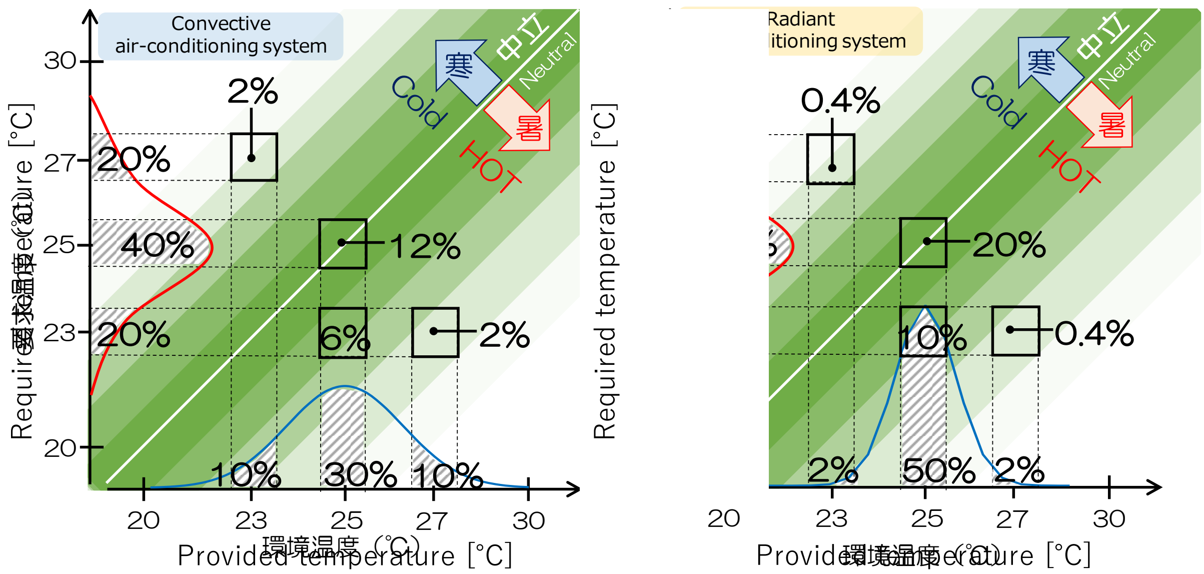


Figure 1. Concept diagram of P-R chart

3. Investigation of required temperature distribution

3.1. Measuring method

The authors surveyed clothing insulation and changes in metabolic rate for individuals in offices aim to calculate required temperature distribution of workers during summer. The clothing rate was evaluated via a questionnaire survey on 1590 workers in nine offices. The metabolic rates of 86 workers in three offices were measured using a physical activity meter (Table 1).

Table 1. Physical activity meter

Appearance	 
Installation	Waist
Measurement interval	10 s

3.2. Clothing insulation of office workers

Figure 2 shows the occurrence frequency of the clothing insulation. The clothing distribution of male workers has two peaks corresponding to a short-sleeve shirt style (0.56 clo) and a long-sleeve shirt style (0.68 clo). The clothing distribution of female workers exhibits more peaks because female workers have a wider range of clothing options. Moreover, females tended to prefer clothing with lower insulation values than males.

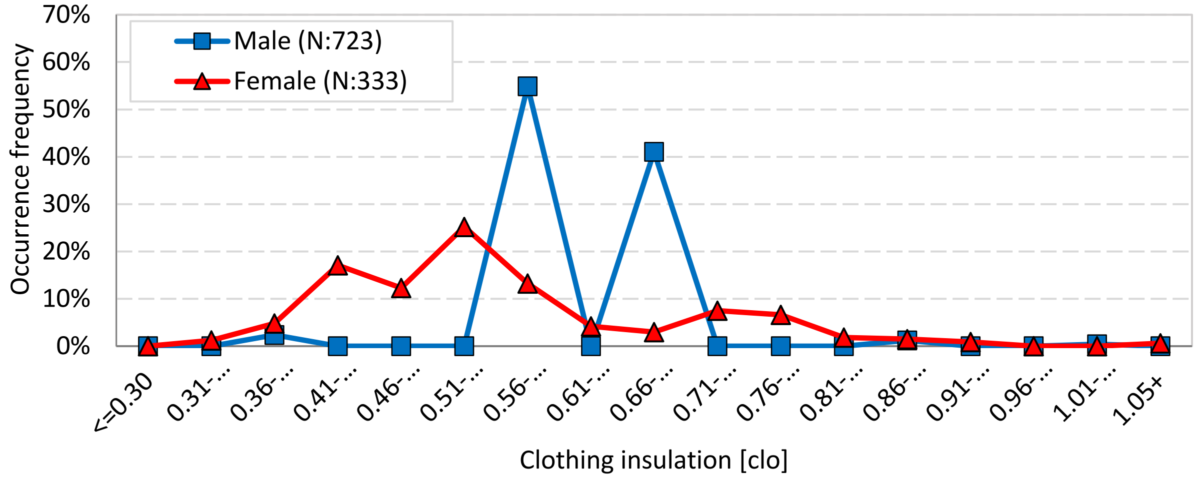


Figure 2. Occurrence frequency of clothing insulation

3.3. Metabolic rate of office workers

Figure 3 shows the occurrence frequency of the metabolic rate from the instantaneous value to the 5-hour movement average value of the workers during business hours. The movement average term is longer and the distribution of metabolic late is more concentrated at 1.1 met. However, in the short term, both the workers whose metabolic rates were low and the workers whose metabolic rates were high were mixed in the same office room.

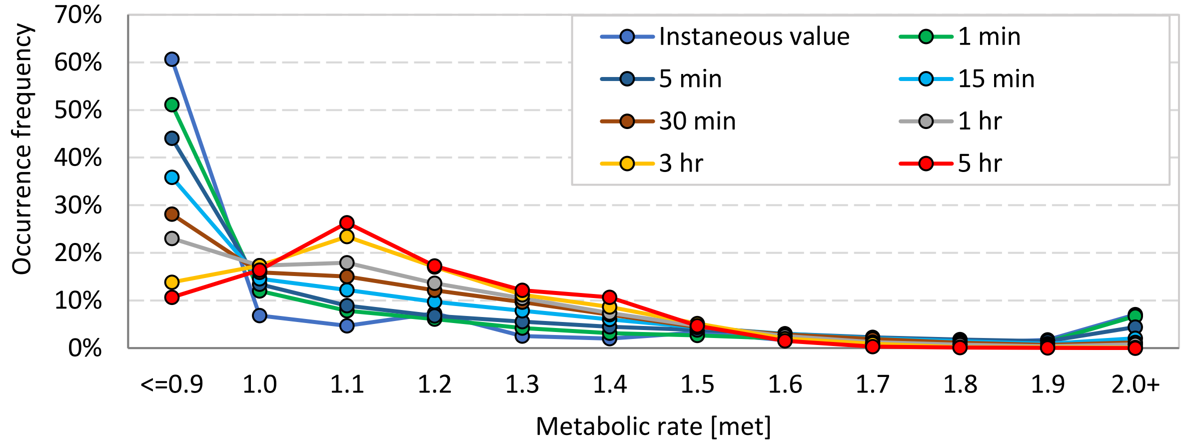


Figure 3. Occurrence frequency of metabolic rate

3.4. Required temperature distribution

In this study, the required temperature was assumed to be the operative temperature at which PMV = 0. Therefore, the required temperature distribution was calculated from the measured clothing insulation (shown in Figure 2) and metabolic rate (shown in Figure 3, assuming a movement average value of 15 min), and assuming a 0.1 m/s air speed and 50% relative humidity. Figure 4 shows the distribution of the required temperature. The required temperature for females tended to be higher than that for males because females tended to prefer clothing with lower insulation values than males. The green line shows the required temperature distribution in the standard office room for an assumed ratio of males to females of 7 to 3. The shape of the required temperature distribution is asymmetrical and very broad on the lower side. Moreover, there is a noticeable difference between the average value (24.7°C) and the modal value (26.9°C). Therefore, even if many workers feel comfortable with the indoor thermal environment, it was presumed that workers' complaints of being too hot occurred more often than workers' complaints of being too cold.

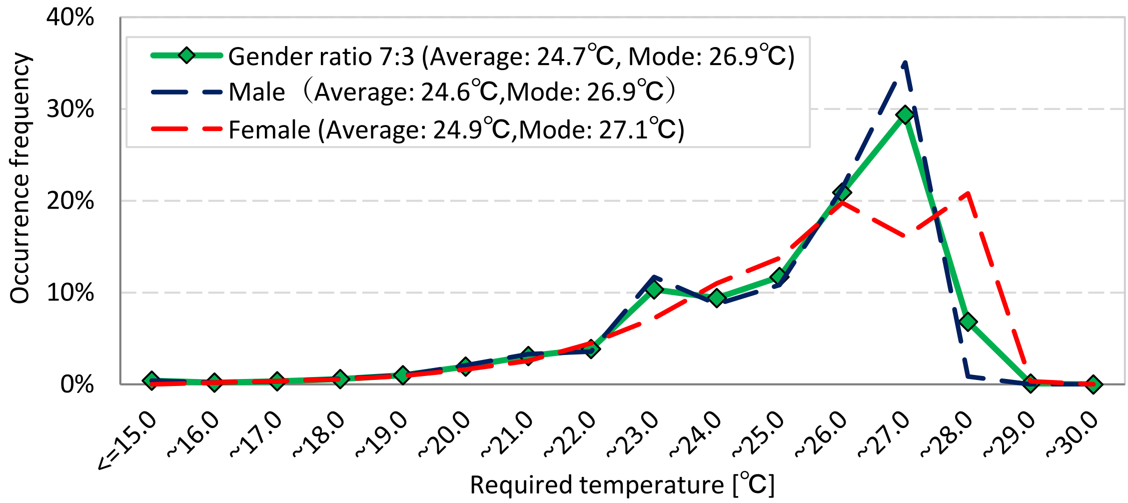
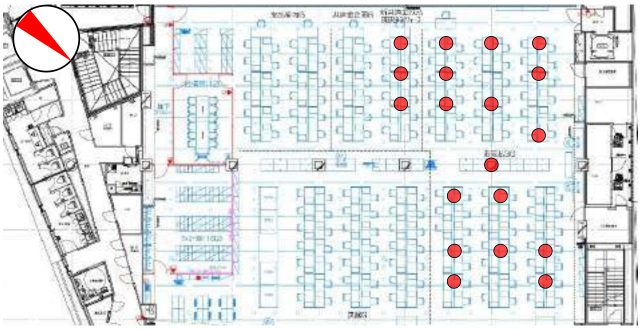


Figure 4. Occurrence frequency of required temperature

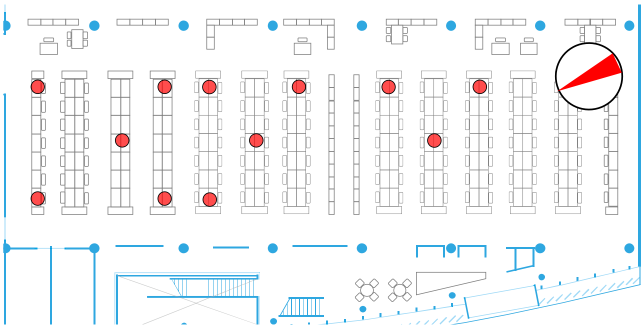
4. Investigation of thermal environmental stabilities in offices with different air-conditioning systems

4.1. Measuring method

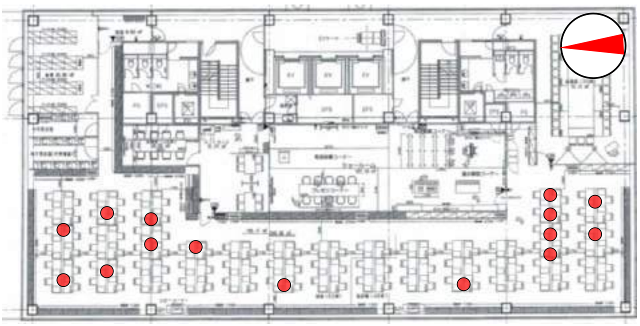
This survey was conducted to characterise both temporal and spatial thermal environmental variations for various air-conditioning systems. Planar thermal deviation was measured during the summer in four offices with different air-conditioning systems. The conditions for each measurement location are shown in Figure 5.



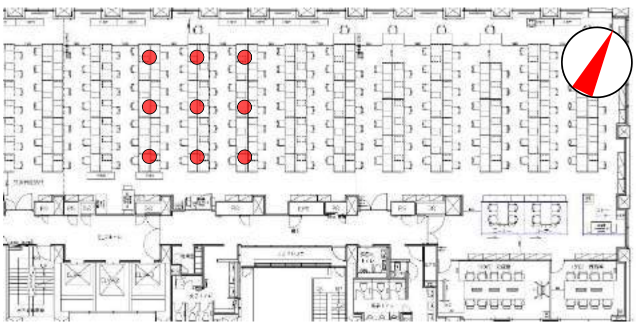
Name	Office N
Location	Tokyo, Japan
Lot area	1,556.80 m^2
Total floor area	8,652.86 m^2
Number of stories	8 stories above ground 2 stories below ground
Structure	SRC
Air-conditioning system	Radiant air-conditioning system + Floor-supply displacement ventilation system
Construction completion year	2015
Survey floor	4th floor
Survey period	August 26–27, 2015



Name	Office T
Location	Tokyo, Japan
Lot area	15,218.23 m^2
Total floor area	8,519.47 m^2
Number of stories	5 stories above ground 1 story below ground
Structure	S
Air-conditioning system	Floor-supply displacement HVAC system
Construction completion year	2014
Survey floor	3rd floor
Survey period	July 25–28, 2016



Name	Office A
Location	Tokyo, Japan
Lot area	2,053.65 m^2
Total floor area	11,527.38 m^2
Number of stories	11 stories above ground 1 story below ground
Structure	SRC
Air-conditioning system	Ceiling-concealed-type multiunit air-conditioning system
Construction completion year	1994
Survey floor	10th floor
Survey period	July 23–24, 2015



Name	Office K
Location	Tokyo, Japan
Lot area	1,347.20 m^2
Total floor area	9,638.88 m^2
Number of stories	8 stories above ground 1 story below ground
Structure	RC
Air-conditioning system	Ceiling-concealed-type multiunit air-conditioning system
Construction completion year	2012
Survey floor	6th floor
Survey period	July 20–22, 2016

Figure 5. Floor plan and thermal measurement points for each office

Office N employs a combination of systems known as a thermally activated building system (TABS). The TABS is a building component in which embedded pipes containing water are used to cool and heat the building. A heat pump is used to transform electrical energy into thermal energy, which is stored in thermally activated concrete slabs. The temperature is managed by air conditioning based on radiation cooling or heating, and humidity is managed by a floor-supply displacement ventilation system using a desiccant. One advantage of the TABS is that the thermal capacity of the slabs is used to reduce peak loads and shift the need for active cooling or heating to different periods of time. Office T employs a floor-supply displacement heating, ventilation, and air conditioning (HVAC) system to control the temperature and humidity inside the office. In this system, cold drafts and nonuniform thermal environments do not occur because the air speed is very slow and air passes through the floor carpet. Offices A and K employ a convective air-conditioning system known as a ceiling-concealed-type multiunit air-conditioning system, in which control of the thermal environment by air turbulence is better than that in a conventional convective air-conditioning system because an anemostat-type diffuser is adopted in the former system. In offices A and K, remote controllers are used to operate the air conditioners. In office K, workers can change the set temperature and the air volume freely. In office A, workers can change only the set air volume. The device used to measure the thermal environment (Table 2) can record the air temperature, globe temperature, relative humidity, and air speed. The locations of the sensors are shown in Figure 5.

Table 2. Details of device used to measure the thermal environment

Appearance	 
Installation	Personal desk
Measurement interval	Air temperature: 5 min, Globe temperature: 5 min Relative humidity: 5 min, Air speed: 1 min

4.2. Thermal environments of offices

Figure 6 shows the data for four offices during operational hours, along with the requirements of ASHRAE Standard 55-2013 for indoor thermal environments. The dashed red lines indicate areas within the comfortable temperature–humidity range in summer. The temperature and humidity were higher than usual, owing to brownout restrictions put in place in the aftermath of the Great East Japan Earthquake of March 2011. Offices A and K (convectional air conditioning) exhibited a wider thermal distribution than office T (floor-supply displacement HVAC) and office N (radiant air conditioning).

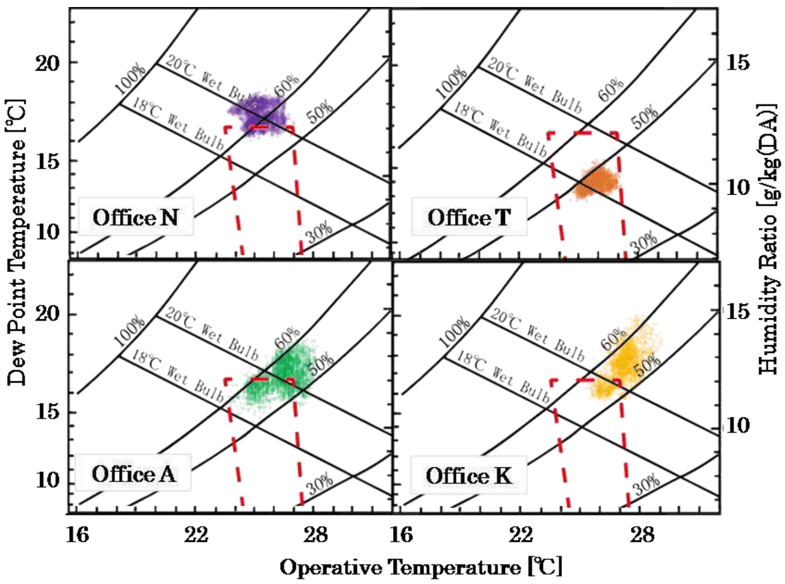


Figure 6. Floor plan and thermal measurement points for each office

4.3. Air speed

Figure 7 shows a boxplot of the air speed in each office during operational hours. No noticeable difference was observed in the average air speed among the offices. However, for the convective air-conditioning system in offices A and K, the air speed exhibited a wide distribution. The figure also indicates that a noticeable difference existed between the maximum and minimum air speeds. In contrast, for the floor-supply displacement HVAC system in office T and the radiant air-conditioning system in office N, the air speed was highly consistent with minimal variation (<0.1 m/s). This minimal variation in the air speed was therefore perceived as being calm in comparison to the air speed variation for the convective air-conditioning system.

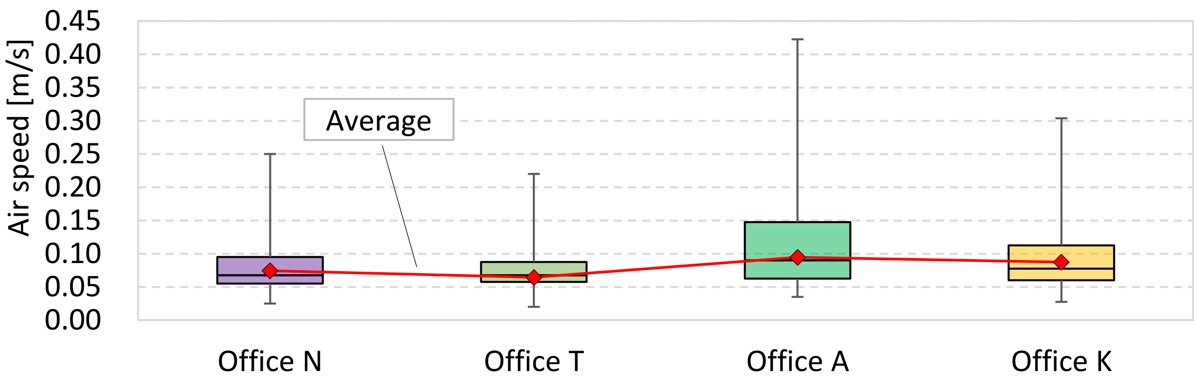


Figure 7. Boxplot of air speed

The percentage of occupants dissatisfied due to draft, expressed by the draft rating (DR (%)), can be predicted by the following equation (Fanger et al, 1985):

$$\mathrm{DR} = (34 - t_a)(v_a - 0.05)^{0.62}(0.37 \cdot v_a \cdot T_v + 3.14) \qquad (1)$$

where t_a is the air temperature [°C], v_a is the air speed [m/s], and T_v is the turbulence intensity of the flow [%].

Figure 8 shows the relationship between the average air speed and the DR for each measurement point for 1 h. The average air speed and DR were concentrated at low values in each office. However, for the convective air-conditioning system in offices A and K, the local air turbulence and DR tended to be higher than those for the radiant air-conditioning system in office N and the floor-supply displacement HVAC system in office T.

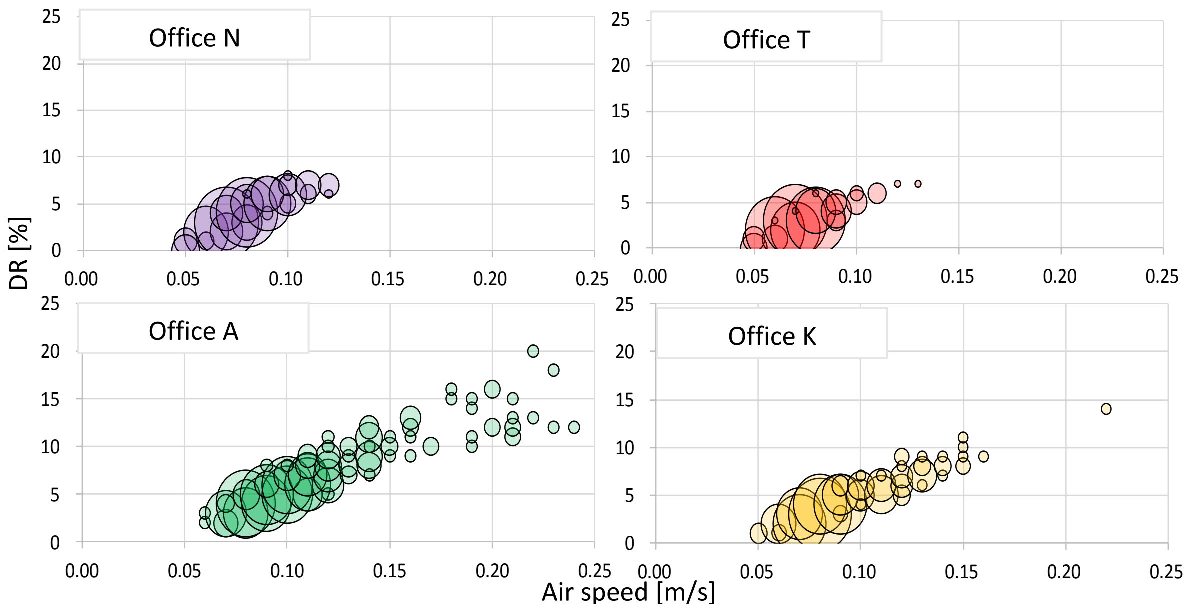


Figure 8. DR value at each measurement point during operational hours

4.4. Equivalent temperature

Figure 9 shows the chronological change in the average equivalent temperature during two representative days. For the convective (multiunit) air-conditioning system in offices A and K, the equivalent temperature repeatedly rose and fell during operational hours. On the other hand, for the floor-supply displacement HVAC system in office T and the radiant air-conditioning system in office N, the air temperature was very stable during operational hours. Considering the characteristics of the TABS in office N, the minimum air temperature was measured beginning in the early morning. The air temperature increased slowly from the morning until noon. Equation 2 is the equation for the equivalent temperature based on the Madsen method (Madsen et al, 1984):

$$t_{eq} = 0.55 \times t_a + t_r + \frac{0.24 - 0.75\sqrt{v_a}}{1 + I_{cl}}(36.5 - t_a) \qquad (2)$$

where t_{eq} is the equivalent temperature [°C], t_r is the mean radiant temperature [°C], and I_{cl} is the clothing insulation [clo] (assumed to be 0.5 [clo]).

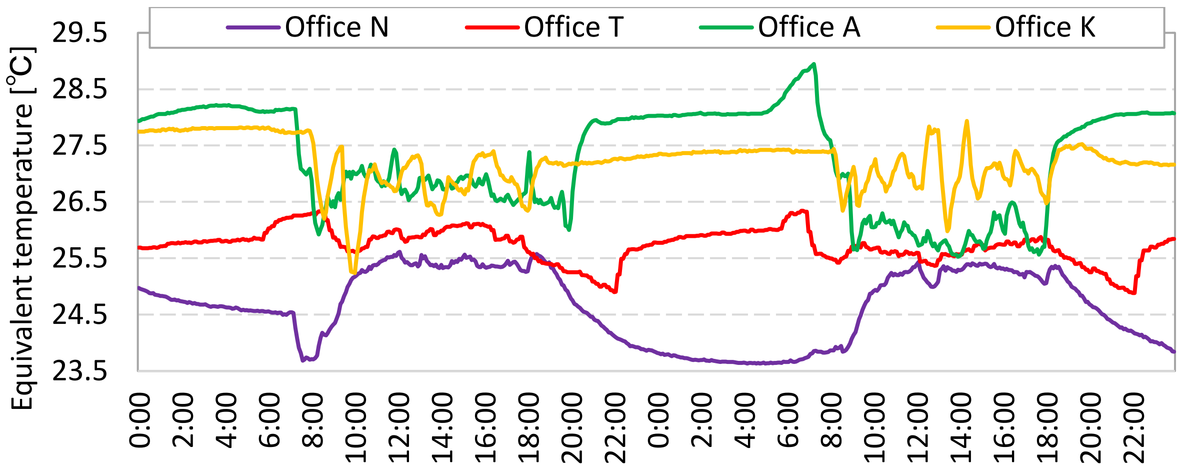


Figure 9. Chronological change in equivalent temperature

4.5. Stability chart

Figure 10 shows the occurrence frequency of the equivalent temperature. Figure 11 shows the occurrence frequency of the divergence between the target set value of the equivalent temperature during operational hours and the instantaneous value of the local equivalent temperature (equation 3). This target set value was assumed to be the average equivalent temperature of all of the measured points during operational hours. The radiant air-conditioning system and the floor-supply displacement HVAC system achieve a narrow distribution of the equivalent temperature and hence provide more uniform thermal environments than the convective (multiunit) air-conditioning system. Therefore, in buildings with convective air-conditioning systems, even if the planar average thermal environment was categorised as comfortable, it was suggested that the workers who were sensitive to cold or heat complained of discomfort more often than those in buildings with radiant air-conditioning systems, because the probability of workers sitting in cold or hot spots increased. Figure 12 shows the chronological change in divergence between the planar equivalent temperature (equation 4) and the planar standard deviation. The authors call this graph a stability chart. In all cases, the planar standard deviation was concentrated at low values during air-conditioning operation downtimes, such as midnight and early morning. In offices A, K, and T, the equivalent temperature tended to be high during air-conditioning operation downtimes, especially early morning. During operational hours, according to the characteristics of the convective (multiunit) air-conditioning system in offices A and K, the equivalent temperature tended to fluctuate considerably and attain high planar standard deviations. Moreover, in office K, the equivalent temperature fluctuated more wildly than in office A because in office K, the workers could change the set temperature. On the other hand, in office N, the equivalent temperature was concentrated at low values during air-conditioning operation downtimes, such as midnight and early morning. In addition, the equivalent temperature did not fluctuate because the temperature in office N was managed by the radiant air-conditioning system; however, the temperature increased slowly from the morning until noon. The equivalent temperature was very stable from noon until night. The thermal environmental fluctuation system in office N is considered to be a typical example of a TABS that uses the thermal capacity of slabs to provide a stable thermal environment.

$$DT_{eq,local} = t_{eq,local,ins} - t_{eq,set} \qquad (3)$$

$$DT_{eq,planar} = t_{eq,planar,ave,ins} - t_{eq,set} \qquad (4)$$

where $DT_{eq,local}$ is the divergence of the local equivalent temperature [K], $DT_{eq,planar}$ is the divergence of the planar equivalent temperature [K], $t_{eq,local,ins}$ is the instantaneous value of the local equivalent temperature [°C], $t_{eq,planar,ave,ins}$ is the instantaneous value of the planar average equivalent temperature [°C], and $t_{eq,set}$ is the target set value of the equivalent temperature during operational hours [°C].

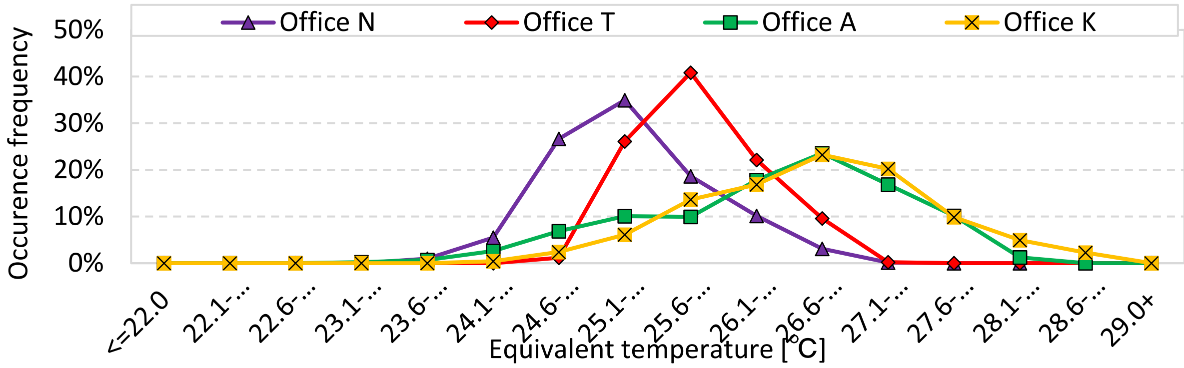


Figure 10. Occurrence frequency of equivalent temperature

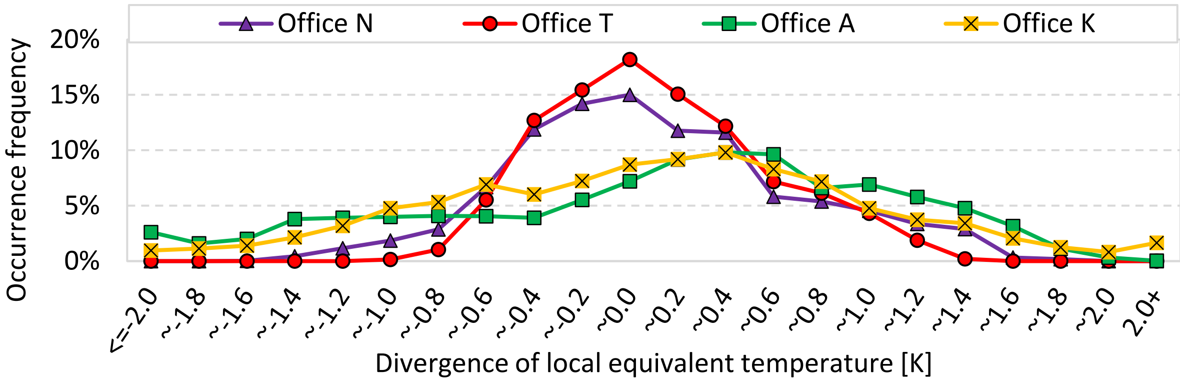


Figure 11. Occurrence frequency of divergence of local equivalent temperature

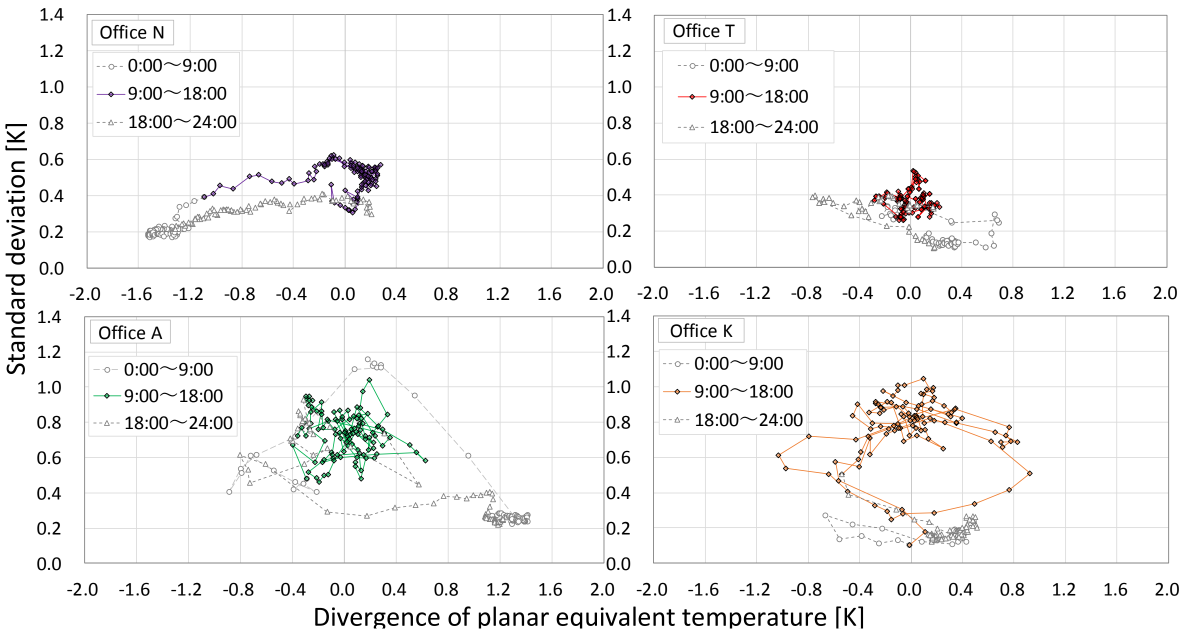


Figure 12. Chronological change in divergence between planar equivalent temperature and planar standard deviation (stability chart)

5. Evaluation of thermal environmental acceptability using P-R chart

Figures 13 to 16 show the P-R chart results for each office. The evaluation of the provided temperature distribution was performed using Madsen's technique for evaluating the equivalent temperature (Equation 2) on a trial basis. On the other hand, the evaluation of the required temperature distribution was conducted in a standard office room by assuming that the ratio of males to females was 7 to 3, as shown in Figure 4, on a trial basis. Office N (with the radiant air-conditioning system) and office T (with the floor-supply displacement HVAC system) had many workers near the thermally neutral line (i.e., the provided temperature being near the required temperature of the workers) because the provided temperature range was narrow. On the other hand, for the convective air-conditioning system in offices A and K, the provided temperature for many workers was different from the required temperature because the provided temperature range was wide. The authors propose an unconformity index (UCI) based on the residual sum of squared differences from the thermally neutral line (at which the provided temperature is equal to the required temperature). When the UCI is higher, more workers who are at the provided temperature have a different required temperature. Office N (with the radiant air-conditioning system) and office T (with the floor-supply displacement HVAC system) had lower UCI than offices A and K (with convective air-conditioning systems). Therefore, in buildings with convective air-conditioning systems, even if the planar average thermal environment is categorised as comfortable, it is presumed that workers who are sensitive to cold or heat will complain of discomfort more frequently than those in buildings with radiant air-conditioning systems and floor-supply displacement HVAC systems, because the probability of workers sitting in cold- or hot-spot areas is higher in the former case.

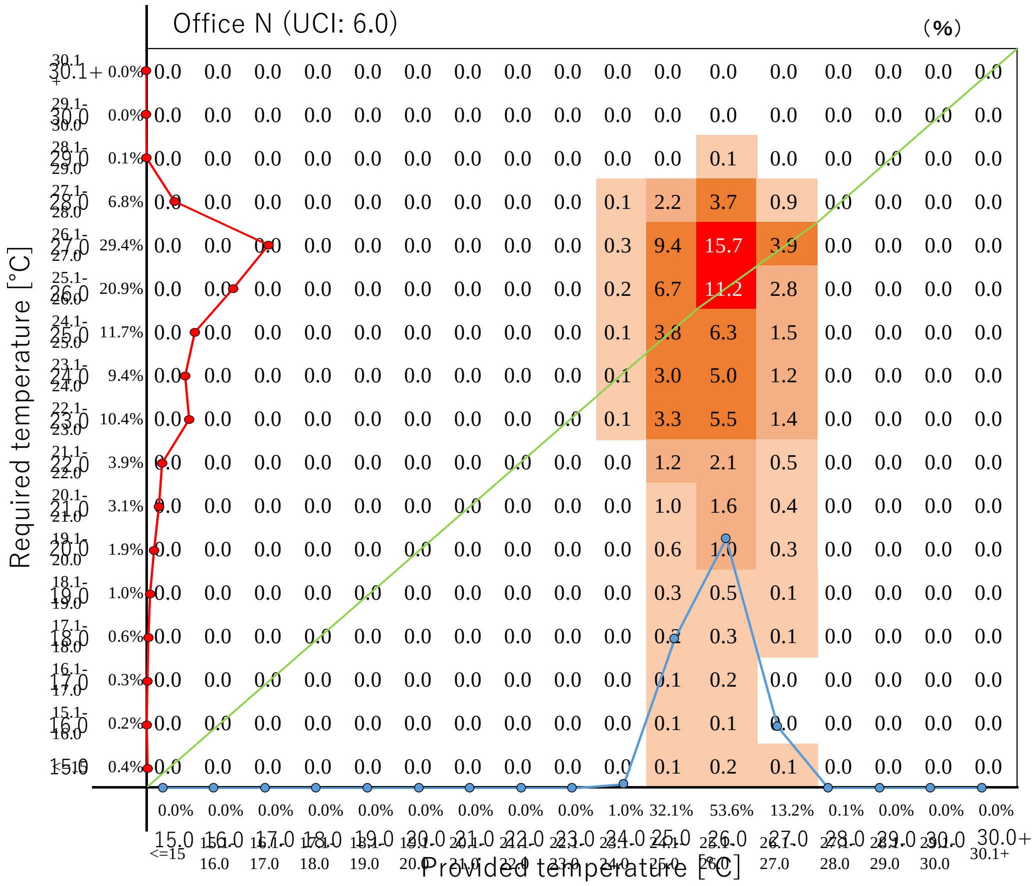


Figure 13. Result of P-R chart for office N (radiant air-conditioning system)

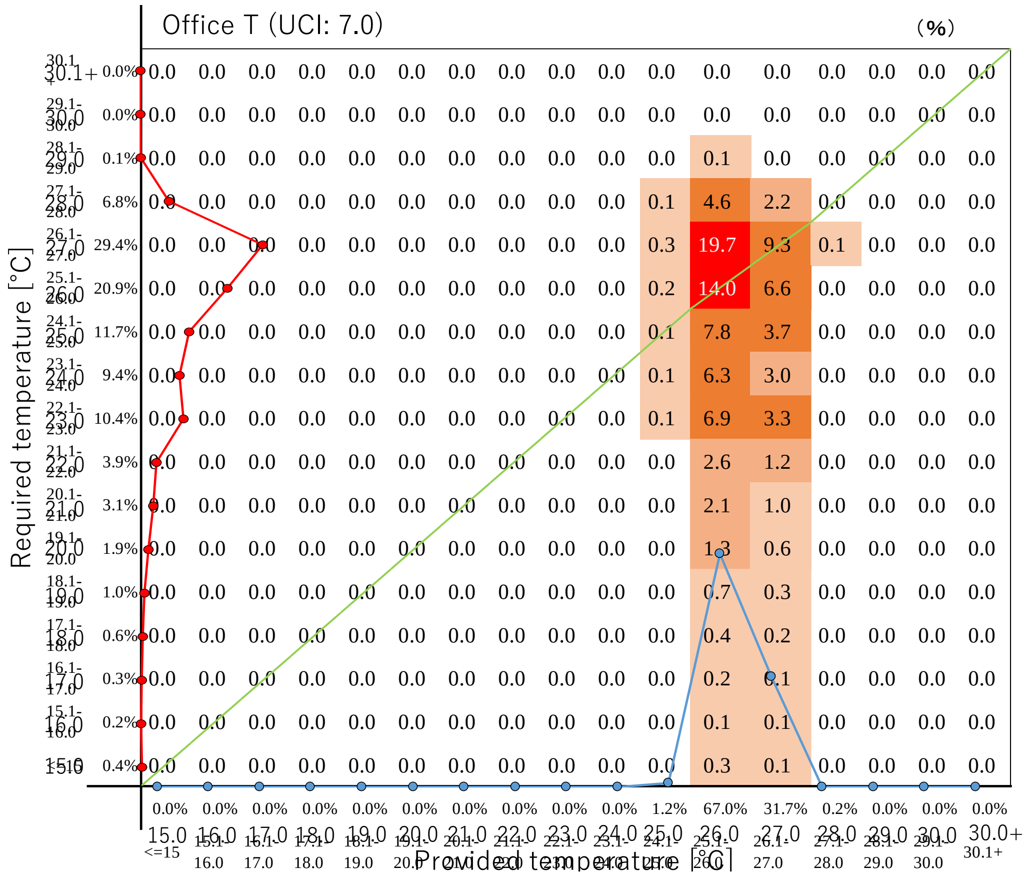


Figure 14. Result of P-R chart for office T (floor-supply displacement HVAC system)

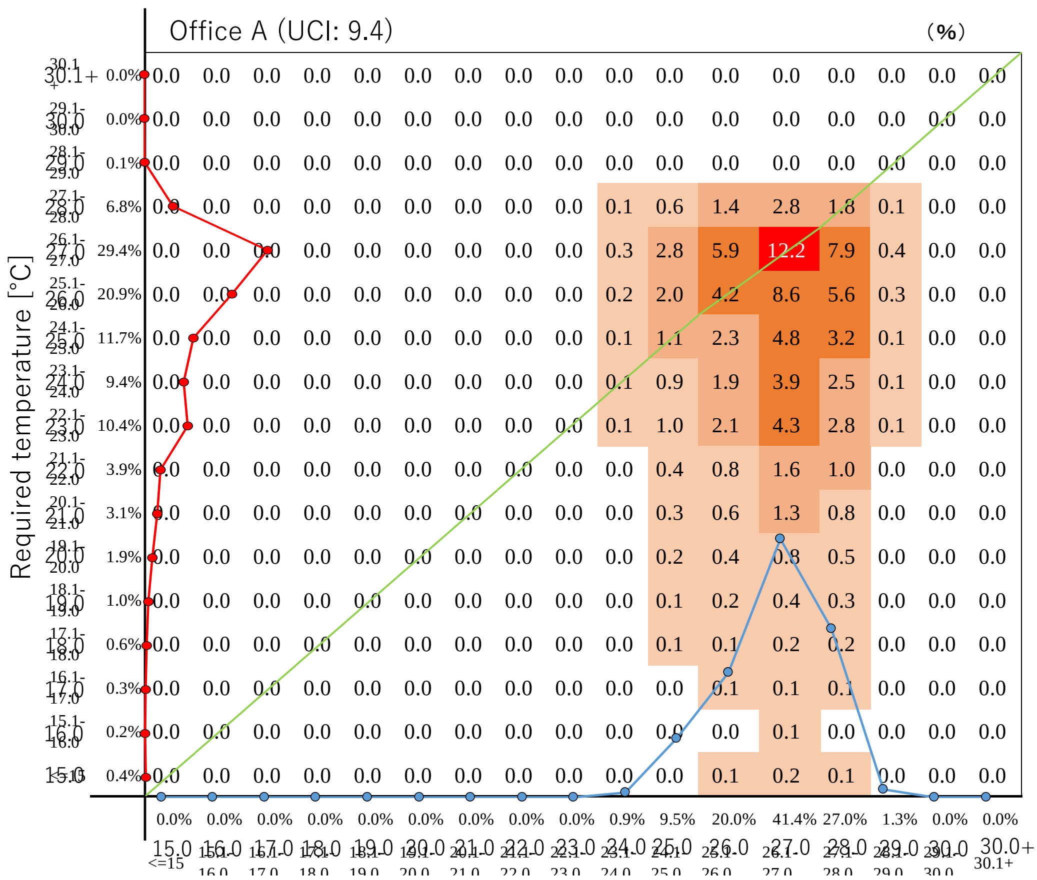


Figure 15. Result of P-R chart for office A (convective air-conditioning system)

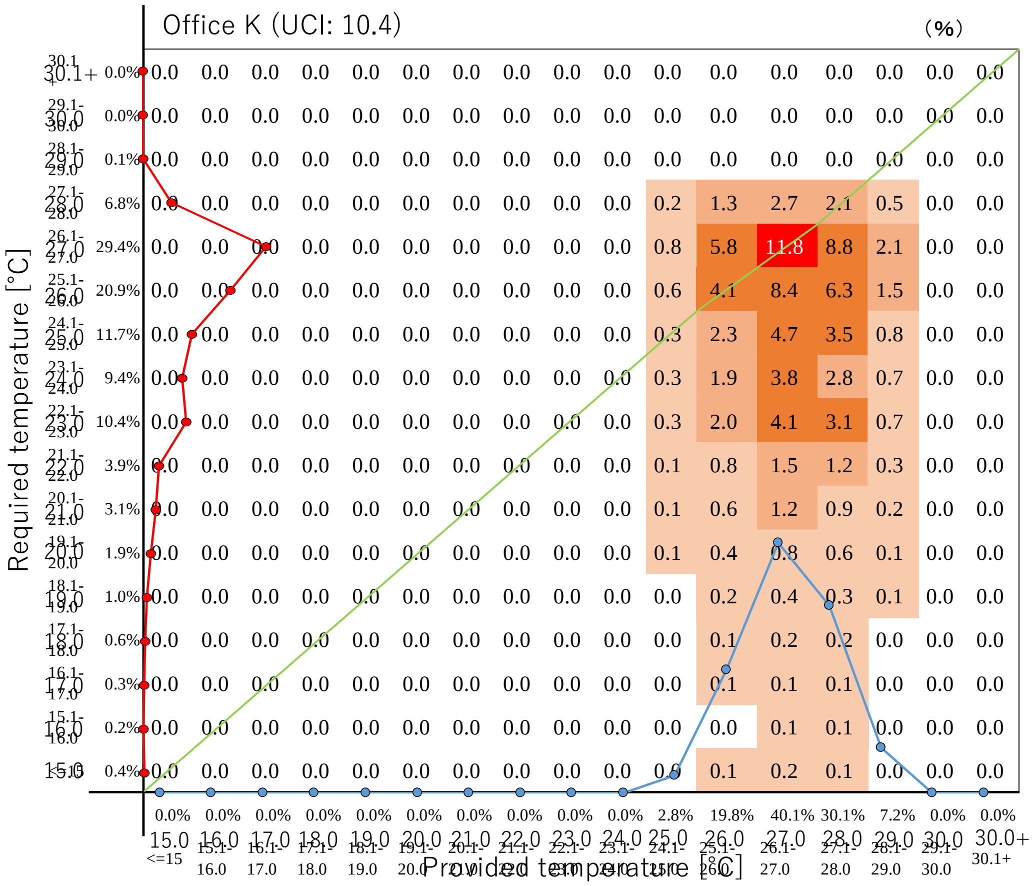


Figure 16. Result of P-R chart fort office K (convective air-conditioning system)

6. Conclusions

This study characterised thermal environmental acceptability for various air-conditioning systems. First, the required temperature distribution of workers was surveyed, and then, the planar thermal deviation during summer was measured in four offices with different types of air-conditioning systems. The authors then characterised both the temporal and spatial thermal environmental variations for the various air-conditioning systems. Furthermore, the thermal environmental acceptability of each of the four offices was also evaluated using a P-R chart. The study results can be summarised as follows:

1) The shape of the distribution of required temperatures for workers was found to be asymmetrical and very broad on the low side. This suggests that even if many workers feel comfortable with the indoor thermal environment, workers' complaints of being too hot will occur more than workers' complaints of being too cold.
2) In the case of the convective air-conditioning system, the findings confirmed a noticeable difference between the maximum and minimum air speeds. In contrast, air speed distributions were narrow for the radiant air-conditioning and floor-supply displacement HVAC systems.
3) The narrow distribution of equivalent temperature indicated that radiant air-conditioning and floor-supply displacement HVAC systems create more uniform thermal environments than convective air-conditioning systems.
4) During operational hours, according to the characteristics of the convective (multiunit) air-conditioning system, the equivalent temperature tended to fluctuate considerably and attain high planar standard deviations compared to the radiant air-conditioning system and floor-supply displacement HVAC system.

5) The P-R chart results for the convective air-conditioning system indicate that many workers find the provided temperature to be different from the required temperature because the provided temperature range is wide.

References

Ukai, M. et al, 2014. Field Study of Thermal Environment Acceptability in Offices Using the Ostracon Voting Device and Seat Occupancy Sensors. *Grand Renewable Energy 2014 Proceedings.* Tokyo, Japan, 27 July–1 August 2014 (in English).

Ukai, M. et al, 2016. A Study on Probabilistic Thermal Acceptability Evaluation. *Proceedings of 9th Windsor Conference*. Windsor, UK, 7–10 April 2016 (in English).

Fanger, P. O. et al, 1985. Comfort Limits for Asymmetric Thermal Radiation. *Energy and Buildings,* 8(3), pp 225–236.

Madsen T. L. et al, 1984. Comparison Between Operative and Equivalent Temperature Under Typical Indoor Conditions. *ASHRAE Transactions,* 90 (I), pp 1077–1090.

How does Passive Chilled Beam system rate from an indoor thermal comfort perspective when compared to Variable Air Volume and Under Floor Air Distribution HVAC systems?

Ashak Nathwani[1]

[1] University of Sydney, School of Architecture, Design & Planning, Sydney, Australia.
ashak.nathwani@sydney.edu.au

Abstract: This study evaluates how Passive Chilled Beam (PCB) system rates in terms of indoor thermal comfort and energy efficiency when compared to Variable Air Volume (VAV) and Under Floor Air Distribution (UFAD) HVAC systems. A human shaped skin-temperature controlled thermal manikin is utilized to directly measure equivalent temperatures (t_{eq}) in a set of adjacent climate chambers that incorporate these three types of HVAC systems. Clothing data was obtained by exposing the manikin to uniform thermal environments. The manikin was moved between chambers subjecting it to non-uniform conditions created by the different HVAC systems, each of which maintained 22.5 +/- 0.5^{o}C. The overall outcome is that UFAD and VAV displayed similar vertical profiles (for a 'clo' value of 0.36) with cooler feet (t_{eq} = 20.9^{0}C & 21.6^{0}C, respectively) and warmer head (t_{eq} = 22.4^{0}C & 22.7^{0}C, respectively). PCB demonstrated relatively warmer feet (t_{eq} = 22.4^{0}C) and cooler head (t_{eq} = 22.1^{0}C). PCB air conditioning system, hence, highlights the adage that cooler head and warmer feet offers better comfort. These are compared with outcomes from similar experiments with human subjects. Energy efficiency values, in the form of energy intensities obtained using thermal modelling analysis, are also presented for the three types of systems with Chilled Beams achieving a 10% advantage.

Keywords: *Thermal Manikin, Equivalent Temperature, Variable Air Volume, Under Floor Air Distribution, Passive Chilled Beams.*

1. Introduction

Integration of an HVAC (heating, ventilation and air conditioning) system into a building design has become an art in terms of meeting the architectural and aesthetic requirements and a science to ensure operational energy efficiency and maintenance of occupant comfort. Proper sizing and selection of the type of HVAC system at the outset has become a crucial step since these systems are recognized as the greatest energy consumers in commercial and institutional buildings (Canbay et al. 2004). Energy costs are often difficult to predict accurately at the design phase of a project when assumptions need to be made about user profiles, occupancy rates, and schedules, all of which impact energy consumption. In many instances where HVAC energy efficiency and associated operating costs are not easily calculable during the selection of these systems, the first selection criterion is often the lowest investment cost (Magdalena S et al. 2013).

HVAC systems can be classified into two – air based and radiant / convective terminals. Air based systems are further divided into supply air being from ceiling or from under floor. For air based systems the room temperature is maintained by controlling the supply air temperature whereas for the radiant and convective systems control of the surface temperature is generally through a water-based system. The heat emission and absorption is fundamentally different in each case, which lead to varying levels of comfort and energy performances. Fluctuations in indoor air temperature account for it to be the most commonly complained item in commercial buildings universally. For office buildings where energy efficiency measures have been adopted indiscriminately, it is becoming more evident that there is increased risk of compromising thermal comfort for building occupants. Against this backdrop it is not surprising that there is an intensification of research activity on the topic of thermal comfort and the overall Indoor Environmental Quality (IEQ) in recent years.

Three HVAC system types are prevalent in commercial buildings in Australia:

- Variable Air Volume (VAV), where the conditioned air volume, generally supplied from the ceiling, varies in response to the heating or cooling load requirements in an occupied zone.
- Under Floor Air Distribution (UFAD), where conditioned air is supplied to an under floor plenum created by raised flooring. Air diffusion is through floor-mounted diffusers.
- Chilled Beam (CB), where cooling is through a cold medium - commonly a chilled water coil, utilising the heat transfer principles of convection and radiation (where exposed). Heating in that case is through heated fresh air or room mounted radiant hot water heaters. Active Chilled Beam (ACB) has supply air outlets (generally conditioned outdoor air) as an integral component that facilitates, via nozzles, induction of room air over the cooling coil and thereby increasing the cooling capacity. Passive Chilled Beam (PCB) is a ceiling mounted unit comprising a cooling coil. There is an independent outside air supply system. In both cases, conditioned outdoor air caters for the mandatory fresh air requirements, latent cooling and heating requirements of the space. ACBs are generally located on the perimeter of buildings whilst PCBs are located in the interior zones.

There is little doubt that the thermal settings presented by HVAC systems, such as ACB & PCB, VAV and UFAD, result in complex, non-uniform thermal exposures shifting the associated research toward non-uniform environments and also providing the impetus for development of multi-node models of human thermal physiology. In line with findings documented by de Dear et al. (2013) this enhanced anatomical resolution of multi-node models enables the subtle nuances of heterogeneous indoor thermal environments and non-steady state exposures to be more realistically captured at the physiological level. *"A pattern has emerged from this short review of thermal comfort of alternative HVAC designs – and that is the paucity of real human subjects in the evaluations, probably reflecting the very large costs of paying subjects for their time, plus the additional complexities of negotiating with human research ethics committees. Instead, most researchers on thermal comfort performance of alternative HVAC systems seem content to trust the comfort predictions of the PPD and PD models, despite the vast body of empirical evidence casting doubt on the relevance of these models to warm environments, which happens to be precisely the context where one would expect to apply 'green' alternative HVAC designs"* (de Dear et al, 2013, page 453).

Research associated with VAV has centred around different types of applications such as occupancy based control strategy for VAV terminal box systems (Liu and Brambley, 2011), optimal terminal box control algorithms for single duct air handling units (Cho and Liu, 2009) and techniques for measuring and controlling outside air intake rates in VAV systems (Krarti et al, 2000). On the other hand, with regards to more recent advancement in ACBs and PCBs and UFAD, there has been a proliferation of research literature involving investigation of these newer technologies and, in a few instances, comparing them with the VAV system. PCBs are increasing in popularity due to the obvious efficiency of not having to transport large volumes of conditioned air around the building. Space efficiency, combined with their energy efficiency and quieter operation, is making them a regular feature of many "green buildings." Laboratory based experiments carried out (Ma J and Zhang Z, 2012) provide details involving combined chilled beams (ACB & PCB) and UFAD, with different supply air temperature, various supply air velocity and changeable temperature of supply water by simulating to cool a small office in summer. Based on similarity theories, some suggestions are given for the numerical area of cooling parameters under some laboratory conditions. However, it does not address any direct comfort issues. Behne (1999) argues, that if the air quality in the occupied zone is top priority and the cooling capacity of a UFAD is not satisfying the load, a PCB can be combined with a UFAD system. Such investigations and outcomes demonstrate a lack of understanding of practical applications, as it is more than likely that such hybrid systems may not be cost effective and have a higher risk of condensation.

The evaluation of HVAC system types cannot solely rely on numerical investigations as several parameters are difficult to model accurately (e.g. interaction between ventilation and terminals, effect of the type of heat source, air temperature stratification). Therefore, full-scale experiments have been performed under both steady-state and dynamic conditions. Thermal manikin and human subjects have been involved in these experiments. This paper focuses on three HVAC systems VAV, PCB & UFAD. The objective of these experiments is to perform a combined evaluation of the energy effectiveness and comfort obtained with the three HVAC systems using the same test facility, specifically with respect to non-uniform indoor environments.

2. Methodology

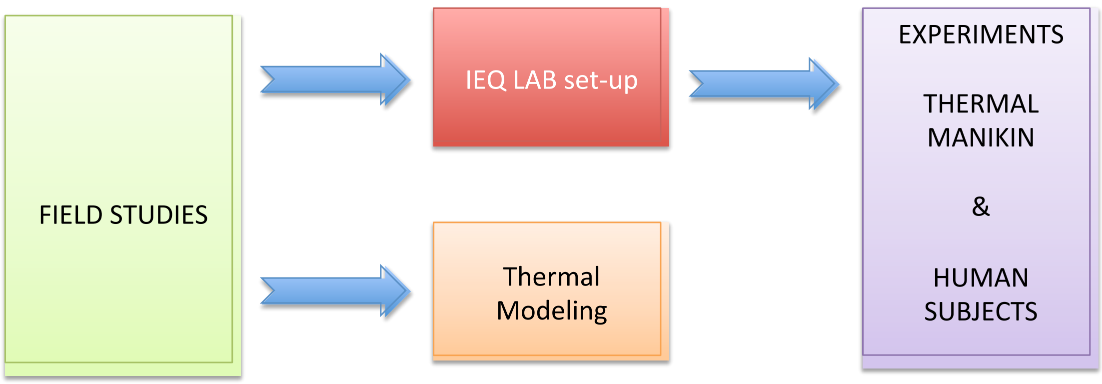


Figure 1. Methodology

The study commenced with field studies whereby nine buildings (three with VAV, three with UFAD and three with ACB & PCB) were evaluated in Sydney, Australia during summer months. The summer period was selected since the contribution of these systems to building energy consumption and variations in indoor air temperatures (resulting in occupant thermal discomfort) are greater during the warmer months. The objective was to obtain data of the three types of systems and replicate them in an IEQ Laboratory, where experiments were carried out using a thermal manikin and later human subjects. Thermal modelling exercises were also carried out on a hypothetical "standard" 10 stories building in Sydney, utilising these three types of systems to compare operational energy efficiencies of these systems in the form of energy intensities.

3. Test Facility

3.1. IEQ Laboratory - Climate Chambers

Technical and physical details of the climate chambers are covered in Nathwani A et al. (2012). The facility comprises two purpose-built climate chambers - Chamber 1 (C-1) and Chamber 2 (C-2), an outdoor simulation corridor and the researchers' control area. Figure 4-2 shows the floor plan and internal views. All of the walls of C-1 & C-2 are double skin with 100mm of mineral wool insulation and plasterboard finish.

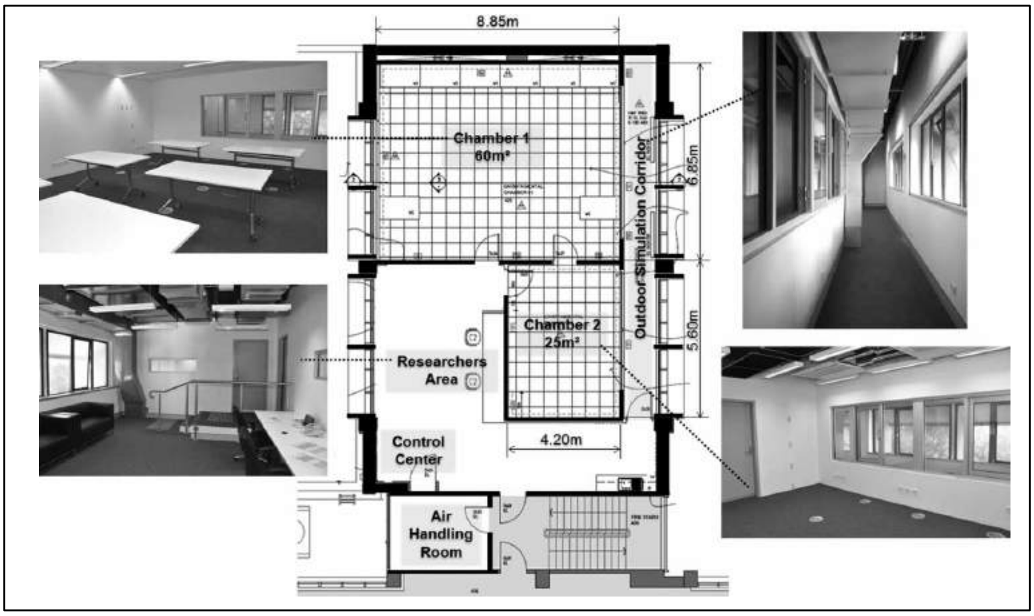


Figure 2. Climate Chambers & Associated Spaces

C-1 is approximately 60 m^2 (8.85m × 6.85m, 2.60m in height with an accessible raised floor of 250mm. The ceiling comprises removable plasterboard 1200 × 600 tiles. C-1 & C-2 so that subjects can move from one environmental condition to the other without being exposed to transients. The climate chambers' fit-out resembles grade-A commercial office spaces (Nathwani et al., 2012). The three HVAC system types under study are available in this facility.

Figure 3. Chambers 1 & 2 – HVAC Systems

3.2. HVAC Technical Data

For C-1, chilled water fan coil unit (FCU-1) provides conditioned air for VAV and the UFAD systems, with appropriate motorised change-over dampers. The air conditioning in C-1 is abled to be switched instantaneously between UFAD and VAV through the building management system (BMS). There are two air conditioning zones in– approximately 35 m^2 on one side (C - 1a) and approximately 25 m^2 on the other side (C-1b). Chamber 1 was partitioned, using moveable screens, to make C-1b comparable to C2 – each approximately 25 m^2. Refer Fig 4 below. This allowed occupation by 3 persons at a time, in each of the chambers, based on approx. 10 m^2 per person, in line with Property Council of Australia Guide (2012).

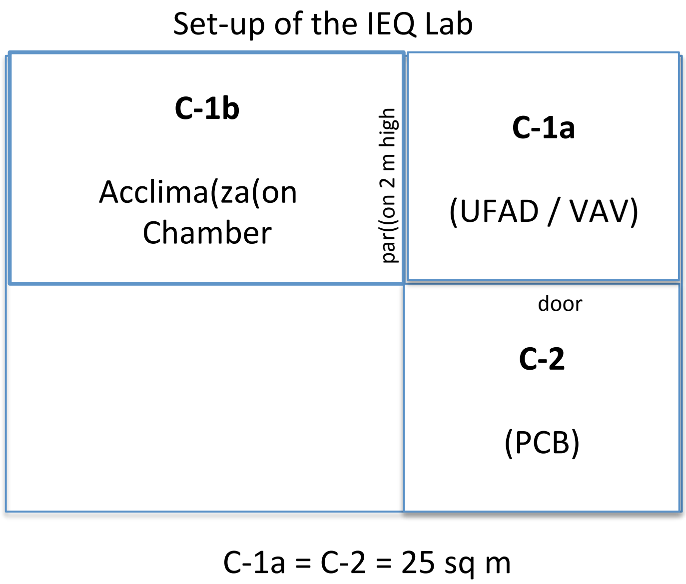


Figure 4. Chamber 1 sub-division C-1a & C-1b & Chamber 2, C-2

2

For the VAV mode, the conditioned supply air volume, supplied at 16^0C, was varied, via motorised VAV pressure-independent boxes, for each zone to meet the specified zone conditions, as dictated by the respective zone thermostats. The air diffusion occurs through linear slot diffusers in the ceiling grid. For the UFAD mode, conditioned air is supplied into the under floor plenum beneath the raised floor, in the appropriate zones. The air is diffused into the zone through swirl-type diffusers located at the floor level. The supply air quantity is based on supply air temperature being set at 19^0C. The return air pathway for both the systems is through slots in ceiling-mounted light fittings, allowing return air to get into the ceiling plenum. Chamber 2 is essentially a single zone (4 m deep) and has the flexibility to simulate an interior or a perimeter zone by selecting passive or active chilled beams (PCB / ACB) respectively. The fresh air quantity for the air conditioning systems was based on the code requirement of 7.5 l/s per person plus chamber pressurisation in each case. Both chambers were set up to simulate *interior zones* of a typical Australian A Grade commercial building. This was based on the fact that evaluation of perimeter zones would have needed to take into account analyses of different building orientations and times of day. This was not achievable in the climate chambers. It is also to be noted that interior zones generally accommodate more of the occupants in commercial buildings. Thus PCB

system, normally used in interior zones, was utilised in C-2 and the VAV and UFAD systems were setup in C-1b in line with data obtained for interior zones from the field studies.
The three HVAC system technical details:

Chamber 1

VAV system settings:

- Airflow range: 8.0 to 4.0 L/s / m^2, supply air temperature (SA): 16^0 C,
  Control algorithm: Proportional + Integral.
- Outside Air = 1.2 L/s per m^2.

UFAD system settings:

- Airflow fixed: 12.0 L/s / m^2, supply air temperature based on re-set schedule:
  Zone Temp = 22.5^0 C, SA Temp = 19^0 C & Zone Temp = 24^0 C, SA Temp = 18^0 C
- Outside Air = 1.2 L/s / m^2.

Chamber 2

- Passive Chilled Beams (sensible): 82.5 W/m^2
- Outside air (sensible and latent): 28.6 W/m^2
- Outside Air = 1.2 L/s / m^2

The set-point for the zoned mounted temperature thermistor sensors – was 22.5^0C +/- 0.5^0C – in line with observations made during the field studies and subsequent investigations of exemplar Sydney office buildings. The lighting levels in each of the chambers were set to 340 lux in line with observations made during field studies.

3.3. Indoor Environment

A dedicated fan coil unit (FCU-2) is employed to provide conditioned outdoor (fresh) air to fan coil unit 1 (FCU-1) as well as the chilled beams. For chamber 2, the zone condition is maintained by utilising the chilled beam (in active or passive mode through change-over valves through BMS). Chilled water valves are modulated to enable this. A secondary chilled water system is utilised to provide the higher chilled water temperatures to the chilled beams in order to prevent condensation on the coils. A building management system (BMS) incorporating direct digital controls (DDC) serves the climate chambers. The BMS logs continuous records of indoor environmental conditions within the occupied zones of the chambers throughout each experimental exposure. The BMS presents a menu-based screen layout with pre-programmed scenarios selectable according to the research design. Each zone in chambers 1 and 2 has sensors for temperature (at various heights above floor: 0.1, 0.6, 1.1 and 1.7m), humidity, carbon dioxide and volatile organic compounds. Following parameters were recorded, every 15 minutes, on the BMS:

- Air temperature in Occupied Zone at 1.1 m above floor level.
- Air Humidity – wall sensor – at 1.7 m above floor level.

Using dedicated sensors and recording equipment, globe temperatures and air velocities were recorded at 1.1 m above floor level in each of the rooms.

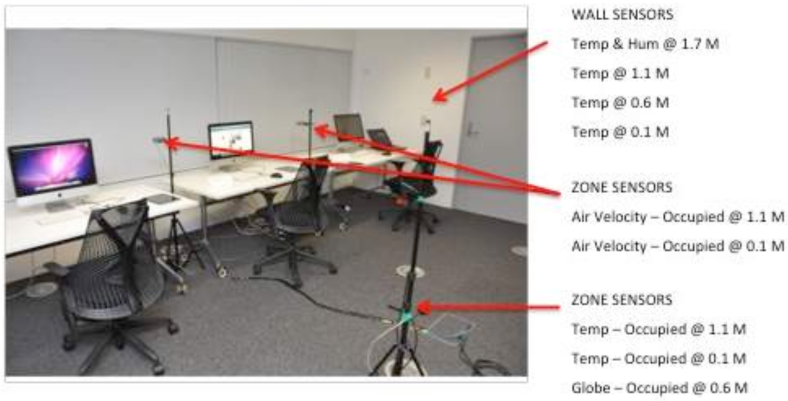


Figure 5. Environmental Measurements - key data.

4. Thermal Manikin

4.1. General

There are various methodological challenges in determining the physiological impacts. One approach is to use a full-size, human-shaped thermal manikin with the surface covered by heating wires and temperature sensors, in order to measure the heat exchange over the whole body and the various body segments (e.g. Wyon et al., 1985, Elnäs, 1988, Nilsson et al., 1993, Tanabe et al., 1994, Bohm, 1999). The heat flow sensors are embedded in the skin of the manikin and measure local heat fluxes of defined areas of the surface. Tanabe et al. (1989) evaluated thermal environments with thermal manikin and determined clothing values under uniform conditions (Tanabe et al., 1994) in line with ISO 9920 and applied these in non-uniform conditions. The measurement technique involved the concept of homogeneous equivalent temperature. It is this method that has been applied for this experiment, using a thermal manikin.

Body Segment	Text	Area (m2)
1	L. foot	0.05
2	R. foot	0.05
3	L. foreleg	0.1
4	R. foreleg	0.1
5	L. front thigh	0.09
6	R. front thigh	0.09
7	L. back thigh	0.09
8	R. back thigh	0.09
9	Pelvis	0.06
10	Backside	0.11
11	Head	0.09
12	Crown	0.05
13	L. hand	0.04
14	R. hand	0.04
15	L. forearm	0.05
16	R. forearm	0.05
17	L. upperarm	0.07
18	R. upperarm	0.07
19	Chest left	0.07
20	Chest right	0.07
21	Back left	0.07
22	Back right	0.07
	Total	1.57

Figure 6. Thermal Manikin – Body Segments & Areas

The thermal manikin, named Laura, is a full-scale dummy that precisely replicates human body and measures power and skin temperature to calculate the insulation and heat loss. It is able to discretise this into great spatial detail through a multi-segmental design. It is anatomically disaggregated into 22 different segments (hands, forearms, upper arms, back, head, crown, thighs, forelegs, feet, etc.), each of which contains a heating element and temperature sensors embedded within the "skin" of the manikin.

The control software is able to heat the manikin to a normal human body temperature, log the amount of power necessary to do so in each zone whilst recording the temperature of that zone. The in-built software provides high-resolution data on heat transfer between the body and the environment. Amongst the outputs from the manikin is the calculated value of the equivalent temperature for each of the body segment.

4.2. Non-uniform Conditions – Equivalent Temperature

Manikin-based equivalent temperature *(t_{eq})* is defined "as the temperature of a uniform enclosure in which a thermal manikin with realistic skin surface temperatures would lose heat at the same rate as it would in the actual environment" (Tanabe et al., 1994). The equivalent temperature is a recognised measure of the effects of non-evaporative heat loss from the human body (Madsen et al., 1984, SAE J2234, 1993, Tanabe et al, 1994, Nilsson et al., 1999). It is particularly useful whenever complex interactions of various forms of heat exchange are present. One main utility of t_{eq} is that it expresses the effects of combined thermal influences in a single figure, easy to interpret and explain. It is particularly useful for differential assessment of the climatic conditions. However, the underlying hypothesis is that the t_{eq} value always represents the same "subjective" response irrespective of the kind of combinations of heat losses. (Nilsson, 2004). This seems to be true, at least for conditions close to thermal neutrality and within limited variations of the climatic factors (Bohm et al., 1990, Schwab et al., 1999).

The following equations (Tanabe et al., 1994) form the basis of the t_{eq} evaluations carried out in this study:

Applying 1 clo = 0.155 m^2 °C/W and *total clothing insulation =* $I_t = (t_{s,cl} - t_a) / 0.155 Q_t$ *, thermal resistance at skin surface per unit total skin surface area (clo) is* $I_a = (t_{s,n} - t_a)/O.155 Q_a$ *(where n = in the nude).*

Thermal resistance at skin surface per unit clothed surface area (clo) is:

$I_{a'} = I_a / f_{cl.}$ *Hence* $I_{cl} = I_t - I_a / f_{cl}$ or $i_t - I_{a'}$ *taking* $f_{cl} = 1 + 0.3\ I_{cl}$ *, hence,*

$$t_{eq} = 36.4 - (0.054 + 0.155\ (I_{cl} + (I_a/f_{cl}))Q_t = Ts - 0.155\ (I_{cl} + I_a/f_{cl})Q_t \quad {}^0C \qquad (7)$$

$$t_{eq(i)} = Ts_{(i)} - 0.155(\ I_{cl(i)} + I_{a(i)}/f_{cl(i)}))Q_{t(i)} \ {}^0C \text{ (where i = individual body part)} \qquad (8)$$

The manikin was used to calculate local (body segment) values of t_{eq} for the various clothing ensembles.

4.3. Clothing Ensembles – steady state conditions

For uncovered legs, manikin was dressed in bra, underwear, skirt, short sleeved shirt and shoes. For covered legs, manikin was dressed in bra, underwear, trousers, three quarter sleeved shirt and shoes. Protocols of ASTM (ASTM-F1291-10, n.d.), and ISO (ISO:9920, 2004) were applied for testing with manikin. *"Clo – constants"* were established as per the protocols>

Figure 7. Manikin Clo = 0.36 Figure 8. Manikin Clo = 0.56

Once stability criteria was attained - 'clo' value was established with chamber equivalent temperature input choosing the 'Parallel' method in the manikin software.

4.4. Test Procedure

Three (3) workstations were set up in each of the chambers as shown below:

Figure 9. Workstation layout – manikin as the third subject.

Experiments, with two human subjects and manikin as the third subject, were from 9.00 am to 6. 00 pm. The experiments for each batch of subjects ran over two (2) days to cater for the two clothing ensembles. Randomisation technique was adopted to allocate seating positions when the subjects, including the thermal manikin, moved from one chamber to the next. The air conditioning system sequencing in C-1b was VAV. After 1 hour the subjects were required to go to C-2 where the air conditioning setting was PCB. After 1.0 hour, the subjects were requested to return to C-1b where the air conditioning setting was UFAD. The subjects were required to spend another hour. After 1.0 hour the air conditioning setting was changed in C-1 to VAV. The same process was repeated in the afternoon but in reverse i.e. starting with UFAD instead of VAV. It is to be noted that manikin was transferred between chambers whilst still energised with the stability criteria remaining within a preset value of 0.1.

This procedure and sequence of movements between the chambers is schematically represented in figure 12 below:

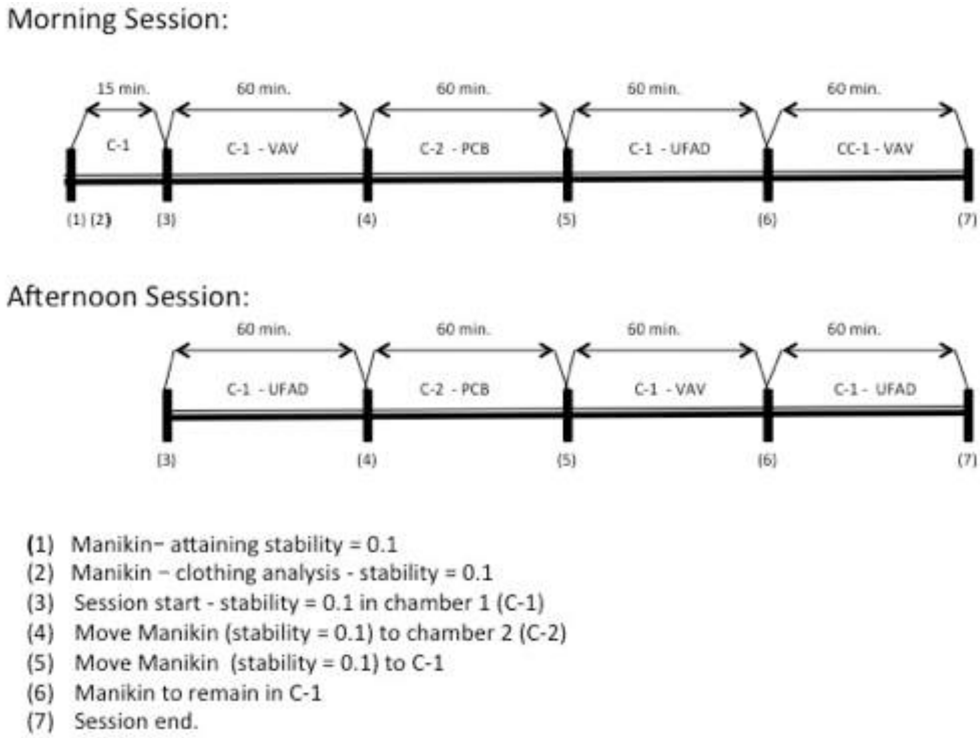


Figure 10. Chambers 1 & 2 – Experiment Procedure

4.5. Measurements

To obtain t_{eq} the actual clo values were taken into account for each of the two clothing ensembles. The inputs for the manikin t_{eq} calculations described in equations 1 through to 8 above were:

- Relative Air Velocity (m/s) = 0.12
- Relative Humidity = 50%
- Barometric Pressure (mm Hg) = 760
- Weight (kg) = 70
- Body Surface Area (m^2) = 1.8
- Metabolic Rate (met) = 1.0

5. Laboratory Experiments involving Human Subjects

5.1. General

Details of the experiment involving human subjects are covered in paper presented at 9th Windsor Conference (Nathwani & De Dear, 2016). Some items are repeated as they have a bearing on the outcomes.

5.2. Test Procedure

Thirty subjects (15 males and 15 females) participated. Participation, with three subjects per day, lasted from 8.30 am to 6.00 pm. The system settings within each room, for each HVAC mode, were based on the data gathered during field studies. Subjects were requested to wear office attire suitable for summer time. The design required subjects to spend specified amount of time in each of the two chambers, where the air conditioning system differed.

Three (3) workstations were set up in the same the arrangement used for previous experiment with thermal manikin. The subjects were not made aware of the type of HVAC system in operation during any of the evaluations. Subjects were requested to carry out their normal work, generally using the allocated desktop computers or their own laptops. The time period was 1.0 hour for each of the air conditioning modes in the two chambers, during which the subjects were required to respond to following question**,** every 30 minutes after move from C-1b to C- 2 and vice-versa.

5.3. Skin Temperature Measurement

Every half hour skin temperatures were taken using an Infrared Digital Camera (FLIR). Various options were investigated for obtaining skin temperature and use of Infrared Digital Camera was chosen on the basis that it was least obtrusive for the subjects.. A Research Assistant carried out the skin temperature measurements. This provided uniformity and consistency in taking the readings. The measurements were taken of the forehead, back of hand and rear left foreleg of each subject and recorded against their allocated codes.

FLIR software was used to obtain the average skin temperatures for each of the measured body segments.

6. Outcomes and discussion

6.1. Clothing Values

Clothing evaluation results:

Table 1 – Clo Values – Day 1 – Legs Uncovered

	DATE	Ta	Ts	Icl	Qt	Teq
Nude, Standing	9/3/2017	22.4	32.5	0	81.7	22.6
Clothed, Standing	9/3/2017	22.4	33.2	**0.36**	64.2	22.5
Nude, Sitting	9/3/2017	22.4	32.7	0	82	22.6
Clothed, Sitting	9/3/2017	22.4	33.3	**0.44**	63.7	22.5

Hence the Clo value for clothing configuration for clo = 0.36 (standing) and 0.44 (whilst seated). The difference (0.08) accounts for the insulation component contributed by the chair.

This compares very well with the ASHRAE Standard 55 – 2010 values:

Bra = 0.01
Panties = 0.03
Skirt Thin = 0.14
Short Sleeve Shirt = 0.17
Shoes = 0.01
Total = 0.36

Weight of the ensemble = 0.38 kg

A linear relationship has been established by some researchers (Hanada, et al., 1983), between the clothing insulation of an ensemble and its weight in grams as I_{cl} = 0.00103 W - 0.0253

Applying the weight, the value is 0.37

For scenario , where the legs were covered, the results are:

Table 2 – Clo Values – Legs Covered

	DATE	Ta	Tskin	Icl	Qt	Teq
Nude, Standing	10/3/2017	22.6	32.6	0	70.5	22.7
Clothed, Standing	10/3/2017	22.6	33.0	**0.56**	52.8	22.5
Nude, Sitting	10/3/2017	22.6	30.9	0	70.4	22.6
Clothed, Sitting	10/3/2017	22.6	32.3	**0.65**	52.8	22.5

Once again comparing to ASHRAE Standard 55 – 2010 values are:

Bra = 0.01
Panties = 0.03
Trousers = 0.24
Long Sleeve Shirt = 0.24
Shoes = 0.01
Total = 0.53

Weight of clothing ensemble in this case = 0.58 kg which equates to Clo = **0.57**

These Clo values were used in the t_{eq} analyses involving the two scenarios. An evaluation of the equivalent temperature difference between the manikin crown and the left foreleg, together with statistical outcomes, was also carried out for the two scenarios.

The results are shown below.

Following are the equivalent temperature (teq ^{0} C) profiles with respect to the body segments for the two clothing scenarios:

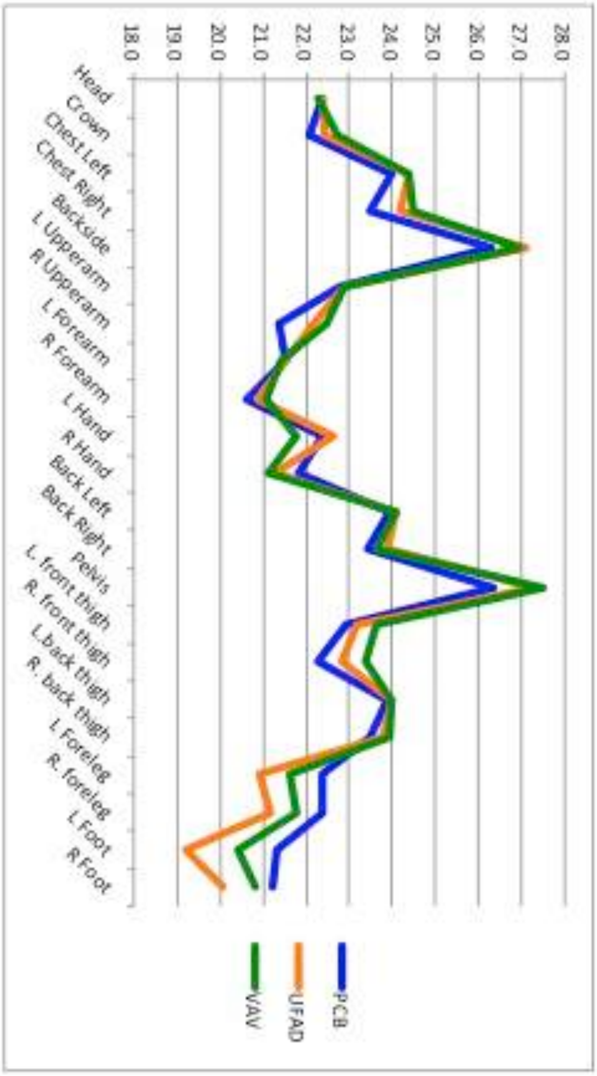


Fig 11. $T_{eq}{}^{0}C$ Profile With Respect To Body Segments For the three HVAC systems Clo= 0.36

The mean t_{eq} for the Crown and L Foreleg for the three air conditioning systems:

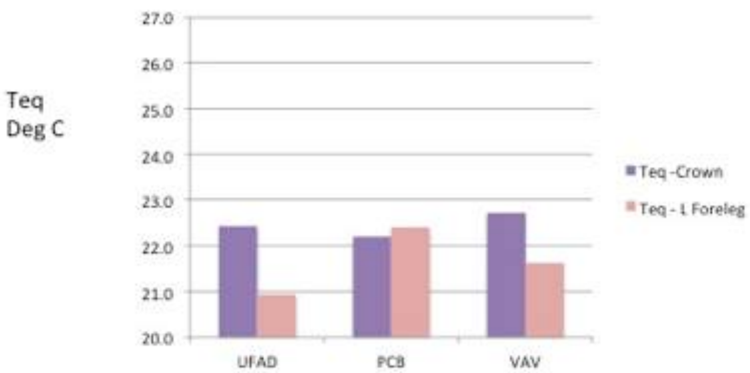


Fig 12 Teq Deg C Crown & L Foreleg – Thermal Manikin - Clothing value = 0.36 – Uncovered legs

Analysis of the equivalent temperature differences for Crown minus the L Leg for the three AC systems:

Table 3. AC System Analysis – Laura – Clothing Value= 0.36 – Uncovered legs

AC System	N	Mean	Std Deviation	Minimum	Maximum
PCB	60	0.29	0.19	-0.6	0.5
UFAD	60	1.14	0.72	- 0.7	2.2
VAV	60	0.79		-0.5	1.8

Test Statistics [a]	UFAD - PCB	VAV – PCB
Z	-6.510 [b]	-6.459 [b]
.	.000	.000

a. Asymp. Sig. (2-tailed)
b. Wilcoxon Signed Ranks Test
c. Based on negative ranks.

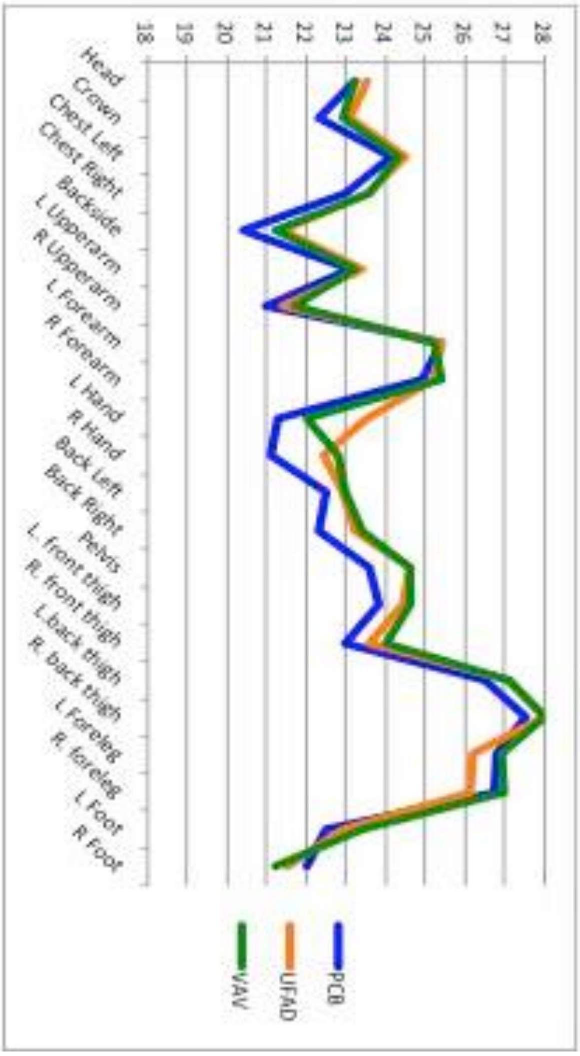


Fig 13. Teq ^{0}C Profile With Respect To Body Segments For the Three AC systems – clo = 0.56

The mean equivalent temperatures for the Crown and L Foreleg for the three air conditioning systems:

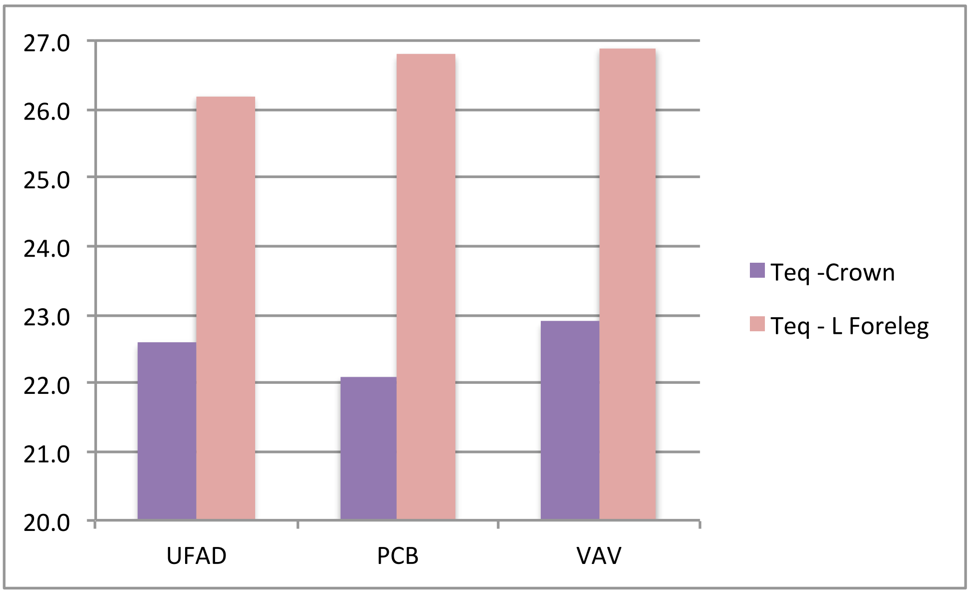


Fig 14. Teq Deg C Crown & L Foreleg – Laura - Clothing value = 0.56 –covered legs

Analysis of the equivalent temperature differences for Crown minus the L Leg for the three AC systems:

Table 4. AC System Analysis – Laura – Clothing Value= 0.56 – Covered legs

AC System	N	Mean	Std Deviation	Minimum	Maximum
PCB	60	-4.49	0.64	-6.2	-3.8
UFAD	60	-4.09	0.46	-4.4	-2.8
VAV	60	-3.19	0.45	-4.3	-2.6

Test Statistics [a]	UFAD - PCB	VAV – PCB
Z	-1.786 [b]	-6.741 [b]
	.000	.000

a. Asymp. Sig. (2-tailed)
b. Wilcoxon Signed Ranks Test
c. Based on negative ranks.

Figs 11 & 13 show the t_{eq} profiles for the two clothing scenarios indicating a warmer upper part and cooler lower part for the VAV and UFAD environments whereas for the PCB it is the reverse. The standards on vertical temperature stratification (ASHRAE, 2013; ISO, 2005) are based largely on experimental research by Olesen, Scholer, & Fanger (1979). As in the earlier research results of Fanger et al. (1980) the source of steady-state discomfort from vertical temperature differences stems from warm discomfort of the head and cold discomfort of the feet. Whilst this is true of air based systems, namely UFAD & VAV, the PCB results tend to agree with Wyon et al.'s (1989) with the comfort 'piste', summarized as 'cool-head and warm-feet'.

Fig 12 confirms the above by highlighting the differences between the Crown and the L Foreleg, in this case being uncovered. Fig 14 also indicates the differences albeit not to the same extent since the clothing value change due to covering of the foreleg plays a vital role.

However applying the analysis, as summarised in Tables 3 & 4, it is evident that the t_{eq} differences between the Crown and L Foreleg for PCB compared to UFAD and VAV are significant. The overall outcome is that PCB has less vertical asymmetry than the VAV or the UFAD. PCB demonstrates relatively warmer feet and cooler head (with least temperature difference between the forelegs and the crown) when compared with the other two systems. Warmer feet and cooler heads offer better thermal comfort preferences as shown with studies involving human subjects.

7. Conclusions

Clothing values (clo) were established for two scenarios and in case the results closely matched with ASHRAE values as well as calculated values, using the weights of the clothing ensembles.

Application of equivalent temperature (teq) based on the thermal manikin for three air conditioning systems was carried out. Teq based on the thermal manikin was shown to be a useful tool with which to detect the effects of asymmetries in non-uniform environments.

UFAD and VAV air conditioning systems displayed a similar vertical profile with cooler feet and warmer head. PCB air conditioning system highlights the adage that cooler head and warmer feet offer better comfort.

8. Acknowledgements

The authors would like to express sincere gratitude to Samim Nathwani for her role as an assistant for the experiments, Nazim Bhimani for the assistance in carrying out the statistical analyses, Dr Mathew Dunn, Dr Thomas Parkinson and Dr Jungsoo Kim for their technical support.

9. References

Arens, E.A., F.S. Bauman,L.P. Johnston, and H. Zhang. 1991. Testing of localized ventilation systems in a new controlled environment chamber, *Indoor Air* 3: 263- 281.

ASHRAE.1989.1989 ASHRAE *handbook--Fundamentals,* chapter 8. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASTM.1991. *ASTM-FI291, Standard test method for measuring the thermal insulation of clothing using a heated manikin.* Philadelphia: American Society for Testing and Materials.

Banhidi, L., S. Somogyi, L. Fabo, and T. Simon. 1991. Compensation of asymetric radiation heat loss to cold walls by different heating systems--Analysis with thermal manikin. *Environment International*17(4): 211-216.

Bauman,F.S., E.A. Arens, S. Tanabe, H. Zhang, and A. Baharlo. Testing and optimizing the performance of a floor-based task conditioning system.

Bischof, W., and T.L. Madsen. 1991. Physiological adaptation of thermal manikins. *Proc. of International Symposium on Man and Environment System '91,* Tokyo,pp. 147-150.

Bohm M, Browén A, Norén O, Holmér I & Nilsson H (1990) Evaluation of the thermal environment in tractor cabs. *International Conference on Environmental Ergonomics IV*, Austin, USA, pp 144-146.

Bohm M (1999) Comparison of Instruments for Measurement of Equivalent Temperature in an Experimental Cab in a Climatic Chamber. *EQUIV Report*, Uppsala, Sweden, No 3.

Canbay, C.S., A. Hepbasli, and G. Gokcen. 2004. Evaluating performance indices of a shopping centre and implementing HVAC control principles to minimize energy usage. *Energy and Buildings* 36(6):587–98.

de Dear R, Arens E & Hui Z (1997) Convective and radiative heat transfer coefficients for individual human body segments. *International Journal of Biometeorology*, Springer, no 40, pp 141-156.

de Dear, R. J., Akimoto, T., Arens, E. A., Brager, G. S., Cândido, C., Cheong, K. W. D., ... Zhu, Y. (2013). Progress in thermal comfort research over the last twenty years. Indoor Air, 23(6), 442–461.

Elnäs S (1988) Thermal climate in confined spaces - Measurement and assessment using a thermal manikin. *SAE-Technical Paper Series*, sae.org, no 881111.

Fanger, P.O. 1970. *Thermal comfort.* Copenhagen: Danish Technical Press.

Fanger, P.O., L. Banhidi, B.W.Olesen, and G. Langkilde. 1980. Comfort limits for asymmetric thermal radiation. *ASHRAE Transactions* 86(2): 141-156.

Fanger, P.O., B.M. Ipsen, G. Langkilde, B.W. Olesen, N.I(. Christensen, and S. Tanabe. 1986. Comfort lirtfits for asynunetric thermal radiation. *Energy and Buildings* 8(3): 225-236.

ISO. 1991. *IS0/DIS-9920, Ergonomics of the thermal environment--Estimation of the thermal insulation and evaporative resistance of a clothing ensemble.* Geneva: International Organization for Standardization.

Kerslake, D.McK.,and J.M. Clifford. 1965. A comparison of the performance of five air-ventilated suits using heated *manikin. N67-10546, Flying Personal Research. Lon*don: Air Force Department, U.K. Ministry of Defense.

Madsen,T.L. 1976a. Description of thermal manikin for measuring the thermal insulating capacity of the clothing. Report No. 48. Lyngby: Technical University of Denmark.

Madsen, T.L. 1976b. Thernmal comfort measurements. *ASHRAE Transactions* 82(1): 60-75.

Madsen, T.L. 1979. Measurement of thermal comfort and discomfort. In *Indoor Climate,* P.O. Fanger and O. Valbjorn, eds., pp. 591-613. Copenhagen: Danish Building Research Institute.

Madsen, T.L., B.W.Olesen, and N.K. Kristensen. 1984. Comparison between operative and equivalent temperature under typical indoor conditions. *ASHRA Transactions* 90 (1): 1077-1090.

Madsen T, Olesen B & Reid K (1986) New methods for evaluation of the thermal environment in automotive vehicles. *ASHRAE Transactions*, ashrae.org, vol 92, part 1B, pp 38-54.

Magdalena Stanescu , Stanislaw Kajl & Louis Lamarche (2013) Simplified optimization method for preliminary design of HVAC system and real building application, HVAC&R Research, 19:3, 213-229

McCullough, E.A., B.W. Jones, and J. Huck. 1985. A comprehensive database for estimating clothing insulation. *ASHRAE Transactions* 91: 29-47.

Melikov A (2003) Breathing thermal manikin for indoor environment assessment - Important characteristics and requirements. *Proceedings of the 5th International meeting on thermal manikins and modelling, 5I3M*, Strasbourg, France, CD cepa.c-strasbourg.fr.

Mihira, K., H. Toda, and H. Arai. 1977. Study on thermal manikin. *Japanese Journal of Human Factors* 13(2): 47-53(in Japanese).

Mitchell, D. 1974. Convective heat loss from man and other animals. *Heat Loss from Animals and Man,*J.L. Monteith and L.E. Mount,eds. London: Butterworths.

Nathwani A, de Dear R, Candido C & Cabrera D (2012) The Next Generation of experientially realistic lab-based research: The University of Sydney’s Indoor Environmental Quality Laboratory, Taylor & Francis. 1-10

Nilsson H & Holmér I (1993) Impact of seat on thermal comfort. *Proceedings of Indoor Air 93: The 6th International Conference on Indoor Air Quality and Climate*, Helsinki, Finland, vol 6, pp 127-132, July 4 - 8.

Nilsson H, Holmér I, Bohm M & Norén O (1999a) Definition and Theoretical Background of the Equivalent Temperature. *Int. ATA Conf, 17-19 Nov*, Florence, Italy, 1999A4082.

Olesen, B.W., M. Scholer, and P.O. Fanger. 1979. Discomfort caused by vertical air temperature differ- ences. In *Indoor Climate,* P.O. Fanger and O. Valbjorn, eds., pp. 561-579. Copenhagen: Danish Building Research Institute.

Olesen, B.W. 1988. How to measure mean radiant-, operative-, and equivalent temperature correctly. *Proc. of 12th Symposium on Man-Thermal Environment System,* Tokyo.

Schwab R & Mayer E (1993) Einfluß der Sonneneinstrahlung auf die ther-mische Behaglichkeit in Kraftfahrzeugen. *FAT-Schriftenreihe*, Holtzkirchen, Germany, Nr 109.

Schwab R, Conrad W & Mayer E (1999) *Correlation Between Objective and Subjective Measurements of Thermal Comfort.* EQUIV Report No 4, Holtzkirchen, Germany, Fraunhofer-Institut für Bauphysik.

Tanabe, S., K. Kimura, and U. Inoue. 1989. Proposal of evaluation method with thermal manikin. *Annual Meeting of Architectural Institute of Japan,* pp. 875- 876.※Toda, K. 1958. Thermal manikin and its application for clothing study. *Japanese Journal of Hygiene*13(1): 146 (in Japanese).※

Tanabe, S., E A Arens, F S Bauman, H Zhang and T L Madsen. 1994. Evaluating Thermal Environments By Using A Thermal Manikin with Controlled Skin Surface Temperature, ASHRAE Transactions 1994 Vol 100 Part 1. 39-48

Winslow,L.E.A., and L.P. Herrington. 1949. *Temperature and human life,* pp. 132-144. Princeton, NJ: Princeton University Press.※Wyon, D.P., and M. Sandberg. 1990. Thermal manikin prediction of discomfort due to displacement ventilation. *ASHRAE Transactions* 96(1).※

Wyon D, Tennstedt C, Lundgren I & Larsson S (1985) A new method for the detailed assessment of human heat balance in vehicles - Volvo's thermal manikin, Voltman. *SAE-Technical Paper Series*, sae.org, no 850042.

Wyon,D.P., S. Larsson, B. Forsgren, and I. Lundgren. 1989. Standard procedures for assessing vehicle climate with thermal manikin. The *Engineering Society for Advancing Mobility Land Sea Air and Space (SAE),* pp. 1-11.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Effects of ceiling fans on the thermal comfort of students in learning environments of Bayero University, Kano, Nigeria

Sani M. Ali[1], Brett D. Martinson[1], Sura Al-Maiyah[2], and Mark Gaterell[1]

[1]Unversity of Portsmouth, School of Civil Engineering and Surveying, Portsmouth, Portland Building, Portland Street, Portsmouth, PO1 3AH, UK;
[2] University of Salford, School of the Built Environment, Manchester, UK.

Abstract: It is well known that thermal comfort is influenced by major physical parameters; air and radiant temperatures, humidity, and air speed in combination with personal attributes; clothing insulation and activity level. Although temperature is conventionally considered in adaptive thermal comfort model, as the most important physical parameter where cooling is involved, moderate air speed can enhance thermal comfort during higher temperatures. Through convective and evaporative cooling, ceiling fans cool people by causing sweat from the occupant's body to evaporate. The northern part of Nigeria, being in the tropics, is known for higher temperature regimes for most part of the year. The use of air conditioning to achieve thermal comfort is not sustainable, for economic reasons and the lack of stable electrical energy. Therefore, a majority of naturally ventilated spaces could be kept thermally comfortable with the control of ceiling fans and operable windows. As part of a research work on learning environments in a Northern Nigerian university, this study reports on the effects of ceiling fans on the thermal comfort perception of the students in two lecture theatres. Air speed, air and radiant temperatures, relative humidity were measured, concurrently comfort surveys were undertaken in the spaces, from which activity levels and clothing insulations were obtained. Adaptive thermal comfort standards, ASHRAE 55 and EN 15251, state that thermal comfort can be maintained as air temperature rises with the use of ceiling fans operating at moderate speed. The results show that reductions of 31% and 22% in overheating from the two lecture theatres were realised, as a result of ceiling fans usage, measured by the degree hour's exceedance indicator. These results were further corroborated by the students' acceptance of thermal conditions of the lecture theatres at temperatures above T_{max}.

Keywords: Ceiling fans, thermal comfort, overheating, Africa, tropics

1. Introduction

There is no rains and no cloud cover in the dry season in Northern Nigeria, resulting in warm weather conditions and making indoor environments thermally uncomfortable. Outside air temperature especially in April can reach as high as 40 °C necessitating the use of air conditioners to keep a cool environment. However, this is complicated by the lack of stable energy supplies in Nigeria (Akande 2010). This makes the use of air movement to facilitate indoor comfort very attractive not only in Kano, a city in Northern Nigeria, but in all hot climates around the world (Nicol 2004). Even before the advent of fossils fuels, human beings learnt the art of excluding the effects of extreme weather from their dwelling units, in high latitude areas and elsewhere, in the cold season fires were kindled, layers of clothing added to keep warm, and massive walls and roof constructed to store and utilize solar radiation. During the hot season however, lighter clothing was preferred, people changed their activities, others slept outdoors and in the daytime tree shades were sought for relaxation and hand held fans were widely used in order to keep cool (Candido, de Dear et al. 2010, Inusa and Alibaba 2017, Li, Zhou et al. 2017). Gradually buildings were made to perform environmentally with natural ventilation through openings; doors, windows and other architectural openings (Candido, de Dear et al. 2010). With the invention of electrically powered fans, ceiling and movable personal fans become popular in the hot and dry climates, and it was only in the first half of the Twentieth Century that air conditioning was invented (De Decker 2014). Although air conditioning (AC) is widely used as a means of meeting thermal comfort requirements where availability and affordability of energy permits, ceiling fans are technically simple, can be operated by non-technical occupants, are inexpensive and with relatively low electrical energy use (Aynsley 2005, Voss, Voss et al. 2013). Zhai et al. (2013) found that the average energy consumed by the fans for maintaining comfort was lower than 10 W per person, making air movement an energy-efficient way to deliver comfort in warm environments. Fans are further different from ACs, because the latter provide a uniform thermal environment in a space, which may not be agreeable to all occupants, while fans, especially personal ones, allow the creation of different micro climates (Zhai, Zhang et al. 2013).

Air velocity is used to influence thermal comfort of occupants by encouraging heat loss from their bodies through convection and evaporation (McIntyre 1978, Schiavon and Melikov 2008). It is also understood from the guidance of TM52 that ceiling fans when operated under moderately controlled air speed, enhances thermal perceptions of indoor occupants (CIBSE TM52 2013). Accordingly, the guidance specifies that an air velocity of between 0.3 m/s and 0.8 m/s, raises the upper comfort temperature boundary (T_{max}). This is reiterated by the ASHRAE standard 55-2013 which states that a controlled increase in air speed from 0.2 m/s to 1.2 m/s in an occupied area raises the upper acceptable operative temperature (ASHRAE 2013).

A research conducted by Aynsley (2005) further suggests that an air speed of about 1 m/s is capable of offsetting a 3°C increase in indoor temperature, and a 3 m/s effects about 7°C . Similarly Nicol & Humphreys (1973) in an analysis on thermal comfort conducted in Northern India and Iraq, found that air movement can result in the reduction of temperature by as much as 4 °C, this was further confirmed by Sharma & Ali (1986) when developing a tropical summer index with Indian subjects. These studies and similar others led the international thermal comfort standards to put forward a relationship between the comfort temperature and the increase in air velocity as demonstrated in Figure 1 (CEN 2007).

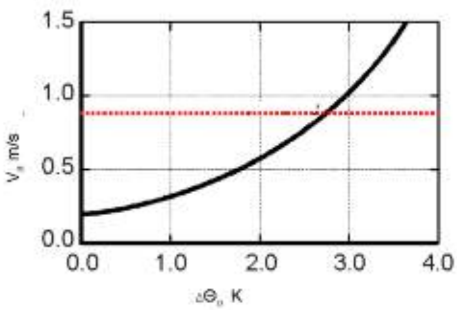


Figure 1: Air speed required to offset increased temperature (CEN 2007)

Ceiling fans are common features of interior spaces in tropical and sub-tropical regions (Nicol 2004, Candido, de Dear et al. 2010). Although the usefulness of ceiling fans is not in doubt, unlike in hot climatic regions, they are not commonly used in the temperate and the higher latitude regions. This could be partly because heating requirements are far greater than the cooling needs. However, some believe e.g. (De Decker 2014), that ceiling fan's usage and popularity were affected by the limit of 0.2 m/s indoor air movement recommended by ASHRAE standard 55 and ISO 7730, which was perhaps introduced to avoid drafts indoors.

This limit is the same the whole year round for both winter and summer seasons. While in the winter, air movement indoors could be counter-productive, it is desirable in the summer. Fortunately, the two last ASHRAE revisions, which brought in ASHRAE 55-2013, took care of the threshold by varying the air speed from 0.2 m/s up to 1.2 m/s, and for higher activity levels over 1.3 *met* there is no limit (Nicol, Humphreys et al. 2012).

Figure 2: Photographs of learning environments furnished with ceiling fans

This paper therefore seeks to further investigate whether ceiling fans could keep the thermal comfort of an indoor environment at a reasonable level and to evaluate the levels of contribution they make in enhancing the thermal qualities of learning environments in Bayero University, Kano. This is to be achieved by evaluating levels of overheating in two selected lecture theatres, through physical measurements and survey data. Figure 2 shows photographs of some learning environments furnished with ceiling fans in the University to facilitate indoor comfort.

2. Fieldwork

The study was carried out in Bayero University, Kano (BUK). Kano, is situated on latitude 12 °N and longitude 8.17 °E, in the Savannah region of West Africa. It is the second largest and most populous city in Nigeria after Lagos. Maximum outdoor temperature reaches 40 °C in April and May and goes down to 12 °C in December and January (Mohammed, Abdulhamid et al. 2015). It receives an average of 3,117 hours of sunlight annually and it is sunny 71% of daylight hours. Relative humidity hovers between 15% and 70% and Kano receives its highest precipitation of about 900 mm in August (Inusa and Alibaba 2017). Being situated within low latitudes combined with high solar radiation and low humidity, Kano region is classified as having a hot and dry climate according to Koppen's classification. Therefore in Kano cooling, minimizing heat gain, diversion of direct sunlight and humidification are required for indoor comfort.

The fieldwork was undertaken from August 2016 to May 2017, and was conducted on three different occasions; during the rainy season of August, 2016 (warm and wet), then in January, 2017 (winter season) when it was cool and dry and finally in May, 2017 (summer season) when it was hot and dry. The selected lecture theatres for the study were chosen from two of the three campuses of the university: New campus and Aminu Kano Teaching hospital (AKTH), and respectively from the Faculties of Earth and Environmental Sciences (FEES) and Clinical Sciences. Therefore for brevity, the new campus theatre will be referred to as “FEES” and the one at the Teaching Hospital as “AKTH”. The characteristics of the theatres are shown in Table 1.

Table 1: Design Characteristics of the Learning Environments

Characteristics of the Lecture Theatres	Capacity (seats)	Volume (m^3)	Floor area (m^2)	Average Height (m)	Window-wall orientation	No. of Ceiling fans	Floor Situation	Window – Wall Ratio
FEES	120	1,368	263	5.2	East/North/West	12	Tiered	30%
AKTH	120	1,829	381	4.8	North/South	14	Tiered	54%

2.1 Physical Measurements

During the fieldworks, both the physical measurements and surveys were conducted based on procedures consistent with ASHRAE standard 55-2013. A number of instruments were used to measure the thermal comfort parameters. Air temperature and velocity and relative humidity were spot measured and only air temperature and relative humidity were logged. Hobo MX1102 were used to log air temperature and relative humidity, 150 mm matt finished globes fitted with Hobo pendants captured the radiant temperature and Testo 435-2 meter was used for air velocity. The spot measurements were conducted in five locations in each theatre at 1.1m above the floor. In the floor plans of both theatres, as shown in the top of Figure 3, measurement locations are shown in coloured letters. Five locations in both theatres containing the “TLCS” were the points of the measurements. The measurements were conducted in two situations, during occupied and unoccupied conditions. Photographs of the interiors of the lecture theatres and external views are also shown in Figure 3.

A B

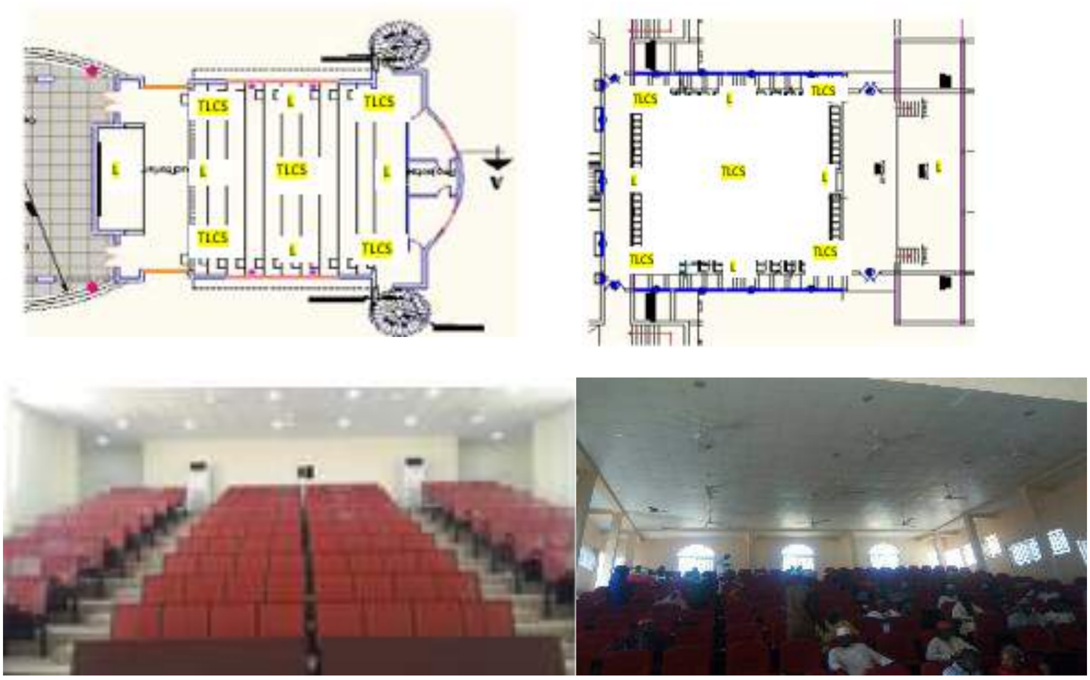


Figure 3: Floor plans, internal and external views of the lecture theatres: A = AKTH and B = FEES

2.2 Subjective Measurements

Paper-based questionnaires were prepared containing seven sections covering; thermal, acoustic and visual comfort, indoor air quality, clothing ensembles, sketches for occupants to indicate their locations and demographic information. As part of an extended PhD work involving an assessment of the indoor environmental quality (IEQ) parameters of various learning facilities, this study is reporting the thermal comfort aspect, which is directly influenced by the air movement. A total of 459 questionnaires (123 and 336 for the AKTH and FEES respectively) were subsequently distributed, filled and collected back, for all the three occasions. Seven point Likert type ASHRAE thermal sensation scales were used to assess both the thermal conditions and the air movement in the spaces as shown in Tables 2, 3, 4 and 5.

Table 2: Thermal comfort acceptability scale

1	2	3	4	5	6	7
Very Comfortable	Comfortable	Slightly comfortable	Okay	Slightly uncomfortable	Uncomfortable	Very uncomfortable

Table 3: Thermal sensation scale

-3	-2	-1	0	1	2	3
Unacceptable	Unacceptable	Acceptable	Acceptable	Acceptable	Unacceptable	Unacceptable
Cold	Cool	Slightly cool	Neither	Slightly warm	Warm	Hot

Table 4: Thermal preference scale

-3	-2	-1	0	1	2	3
Wanting cold	Wanting cool	Wanting slightly cool	Wanting no change	Wanting slightly warm	Wanting warm	Wanting hot

Table 5: Air movement acceptability scale

-3	-2	-1	0	1	2	3
Too draughty	Draughty	Slightly draughty	Okay	Slightly still	Still	Too still

Both the physical measurement and the survey results were used in evaluating the thermal conditions of the two theatres by following the grouping method system adopted by Al-Maiyah, Martinson and Elkhadi (2015). The 7-point scale was converted into three-point scale by merging the responses in the first two categories into one 'comfortable' category and merging the last two categories into 'uncomfortable' while the three central categories formed the 'moderately comfortable'. Similarly the recommendations of ASHRAE Standard 55 (2013) and CEN 15251 (2007) were followed. Further to this, degree hour's exceedance, an indicator of overheating, was used to determine the deviation of thermal conditions in the theatres from the CEN 15251 adaptive comfort threshold. The predicted mean vote (PMV) model and adaptive approach using operative temperature were also employed in the analysis. Similarly the chart in Figure 1, relating the air movement and comfort temperature, was used to determine the likely contribution of the air velocity to comfort in the spaces. The values of the measured and derived thermal comfort parameters found in the spaces are displayed in Table 6. It is worth noting however that, the air temperature, relative humidity and air velocity measurements in the spaces were for occupied situations, the unoccupied values are not very critical for this study, because ceiling fans were seldom used during the winter in Kano, as shown by the low air velocities.

Table 6: Measured and Derived Thermal Comfort Indices

Parameters/Theatres	FEES			AKTH		
	Aug/Sept (warm & wet)	Jan/Feb (cool & dry)	Apr/May (hot & dry)	Aug/Sept (warm & wet)	Jan/Feb (cool & dry)	Apr/May (hot & dry)
Air temp (˚C)	26.80	29.20	34.40	27.20	25.30	35.60
Standard deviation	0.82	0.31	0.25	0.73	0.44	0.26
Air velocity (m/s)	0.61	0.04	0.65	0.58	0.06	0.63
Standard deviation	0.05	0.03	0.06	0.07	0.04	0.05
External air temp (˚C)	30.40	26.40	34.80	27.90	25.40	36.50
Standard deviation	1.28	0.74	1.72	1.95	0.61	1.76
Relative humidity (%)	69.60	16.00	41.90	60.20	18.30	36.40
Standard deviation	2.48	1.03	2.29	1.06	1.87	2.52
Clothing insulation	0.66	0.72	0.65	0.65	0.71	0.60
Operative temp (˚C)	26.97	29.51	33.36	27.30	25.60	35.00
Standard deviation	0.39	2.13	1.87	0.51	1.75	1.76
Operat. temp (no fan) (˚C)	27.10	29.45	32.55	27.45	25.60	34.55
Standard deviation	0.30	2.25	1.86	0.42	1.77	1.72
Running mean temp (˚C)	27.40	26.80	34.40	27.40	25.40	36.50
Predicted mean votes	0.24	1.35	1.56	0.36	0.38	2.02
Actual mean votes (AMV)	0.57	-0.78	1.34	0.46	-1.03	1.49
Standard deviation	1.54	1.30	1.02	0.85	0.69	0.96
Neutral temp (˚C)	27.80	26.70	30.20	27.80	27.20	30.80
Comfort temp range (˚C)	24.8-30.8	23.7-29.7	27.2-33.2	24.8 – 30.8	24.2-30.2	27.8-33.8

3. Measured results

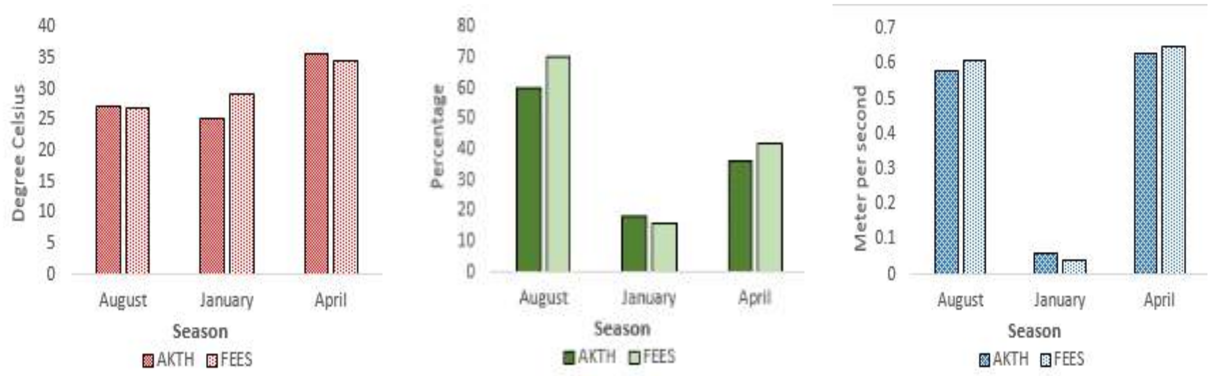
The air, mean radiant and external temperatures, air velocities and relative humidity are the main parameters measured and reported in Table 6 above. The table also contains values that were derived, including operative temperature (T_{op}), running mean temperature (T_{rm}), predicted mean vote (PMV), the adaptive neutral temperature (T_{comft}) and comfort temperature range, similarly fan modified neutral and comfort temperature range are shown. Other derived values from the questionnaires include: actual mean vote (AMV) and actual percentage dissatisfied (APD), which are processed from the results of the answers obtained from the survey questionnaires.

The operative temperature (T_{op}) is an important parameter in assessing the likely thermal comfort of the occupants of a building, known as dry resultant temperature, but renamed as operative temperature to align with ASHRAE and ISO standards. It is a simplified measure of human thermal perception of temperature derived from mean air temperature, mean radiant temperature and air speed (see Equation 1). Where the air speed is less than 0.1m/s, the radiative and convective heat transfers may be similar, so T_{op} becomes the average of the air and mean radiant temperatures (Nicol, Humphreys et al. 2012). The calculated T_{op} with and without the influence of fans are also shown in Table 6 above.

$$Top = \left(Tmr + \frac{Tar \times \sqrt{10Va}}{1+\sqrt{10Va}}\right) \qquad \text{Equation 1}$$

Where T_{ar} is the air temperature, T_{mr} is the mean radiant temperature and V_a is the air speed (m/s).

The operative temperature values were obtained by processing the values of air and mean radiant temperatures in Equation 1 above and were used to determine the adaptive thermal comfort temperature ranges and neutral temperature. PMV was calculated using the Centre for the Built Environment (CBE) thermal comfort tool for ASHRAE, the clothing insulation (*clo*) values were obtained from the questionnaires while the metabolic rate (*met*) of 1.2 *met* for seating and listening was used (Tyler 2013). AMV is the mean of the thermal sensation votes of all participants of a survey in a real world setting as opposed to PMV, which is laboratory based. As mentioned earlier, this study combined the three central categories (-1, 0 & +1) of the thermal sensation scale and assessed them as acceptable, while the APD was calculated from the share of the two extreme categories (-3 & -2) and (+2 & +3) from the thermal sensation votes.



A - Air Temperature B - Relative Humidity C - Air Velocities

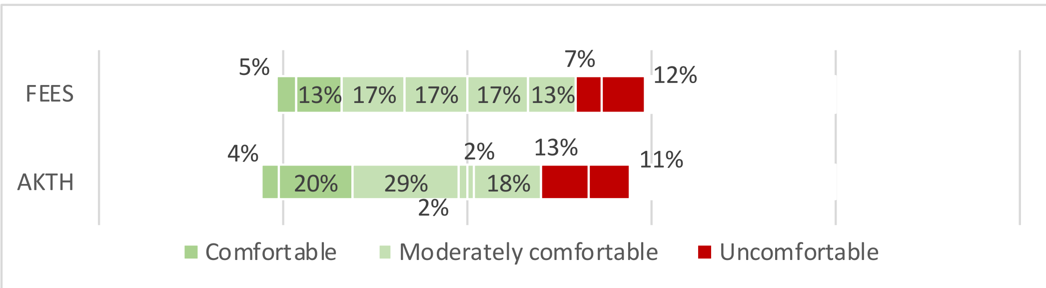
Figure 4: Seasonal Air Temperatures, Relative Humidity and Air Velocities in the Theatres

Table 6 and Figure 4 reveal that the April air temperature values were the highest in both theatres, as was expected, it was the hottest period of the year in Kano, with the air temperature reaching as high as 35.6 ˚C and was recorded in AKTH. It is understood from the table that the internal air temperatures were following the external temperatures in the spaces during mid-season and summer, but that was not the case for FEES during the winter. The air velocity values recorded were both highest and lowest in FEES, and were expectedly higher in April and lowest in January, when fans were not operated, they stood at 0.65 m/s (SD = 0.06) and 0.04 m/s (SD = 0.03) respectively. The design capacities of the two theatres are equal: that is 120 seats, but the occupancy levels during the surveys were different. AKTH was occupied by about one third of its design capacity across the three surveys, while FEES was full to its design capacity on all the three occasions.

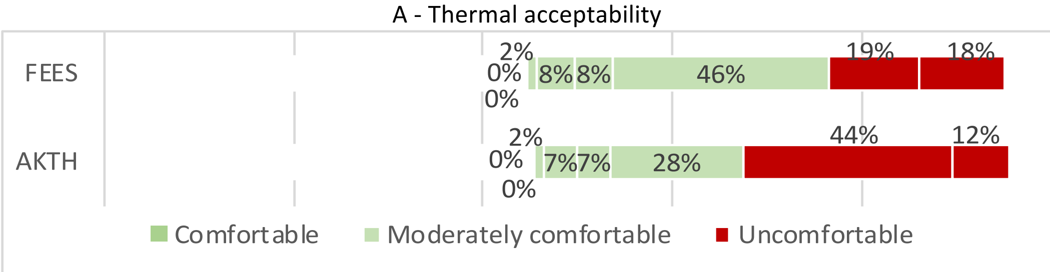
4. **Survey results**

The surveys were undertaken across in the three seasons, females accounted for 22% of the students-dominated respondents and 75% of them were 26 years and above. From the clothing ensembles section of the questionnaire, *clo* values were found to differ across the seasons. The highest mean value of 0.72 *clo* (SD = 0.13) was recorded in January and the least of 0.60 *clo* (SD = 0.11) was recorded in April. Whereas metabolic rate for lecturing and listening was fixed at 1.2 *met*.

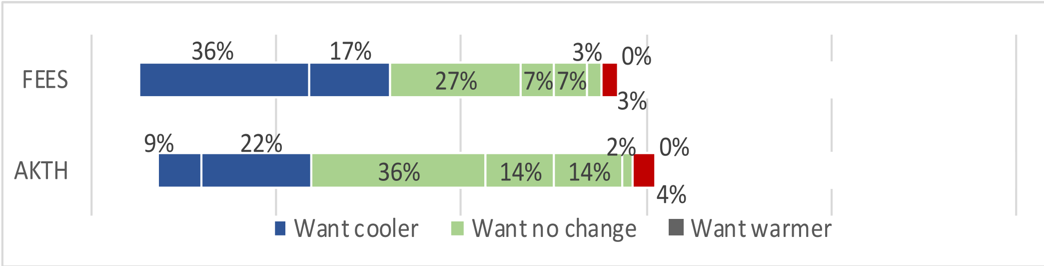
It is during the summer that the effect of high temperature is more problematic in the Kano region, therefore the analysis of the possible overheating using the subjective votes was restricted to the summer results only. It is also noteworthy that during this season ceiling fans were operated practically in every naturally ventilated building in the region, therefore the thermal acceptability levels in both spaces were calculated based on this fact. The levels of thermal acceptability shown by the respondents in AKTH and FEES were respectively 75% and 81%. Indoor climates of the learning environments during the survey were on average four degrees warmer than the ASHRAE comfort standard prescriptions but caused less thermal discomfort than expected. However despite the high levels of acceptance, 56% and 37% of the respondents reported that the theatres were respectively "hot". On the question of their preferences, 30% in AKTH and 53% in FEES preferred cooler environments, and surprisingly up to 5% of them in AKTH wanted to be warmed. In AKTH up to 96% of the respondents were happy with the air speed of 0.63 m/s while 80% showed their acceptance of 0.65 m/s air speed in FEES. Figure 5 shows the thermal acceptability, sensation, preference and acceptability of air movement of the students in both theatres during the season.



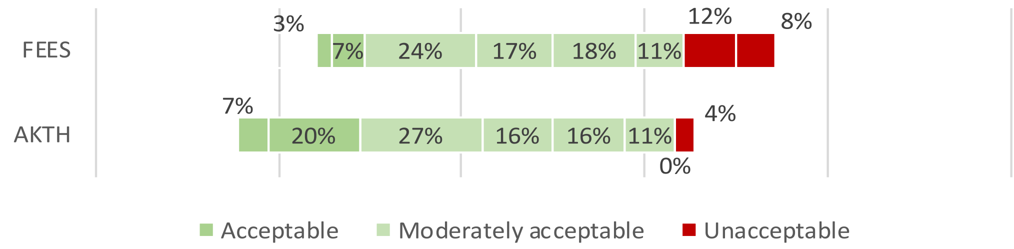
A - Thermal acceptability



B – Thermal sensation



C – Thermal preference



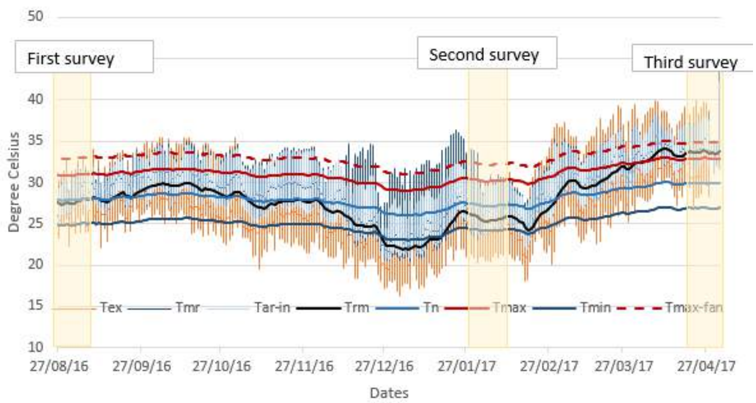
D – Air movement

Figure 5: Thermal Acceptability, Sensation and Preference and air movement during the Summer

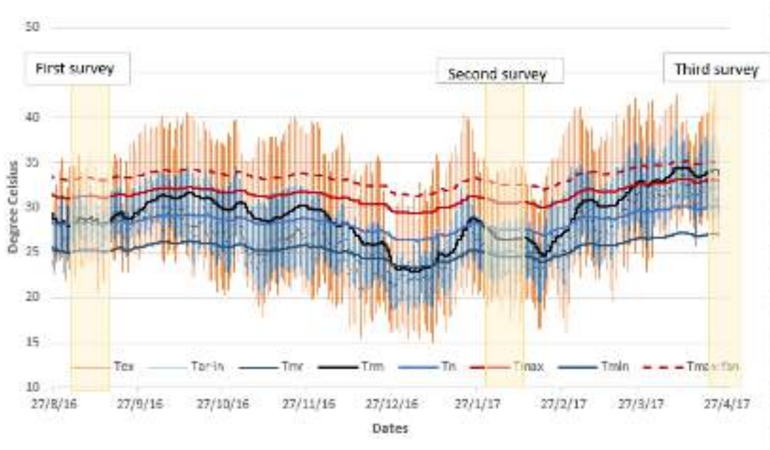
5. Overheating Analysis

A space is said to be overheated during the occupied hours when the operative temperature exceeds a threshold comfort temperature. Similarly the severity of the overheating in any given day is a function of its duration and a rise in temperature above the threshold (CIBSE TM52 2013). TM52 (2013) offers a pass mark to any indoor space that meets any two of the following three criteria:

- Threshold temperature should not be exceeded by more than 3% of occupied hours per year;
- Daily weighted exceedance shall be less than or equal to six degree hours; and
- Operative temperature not exceeding the threshold upper limit (Tupp).



A - AKTH temperature time series



B - FEES temperature time series

Figure 6: Temperature time series of the theatres

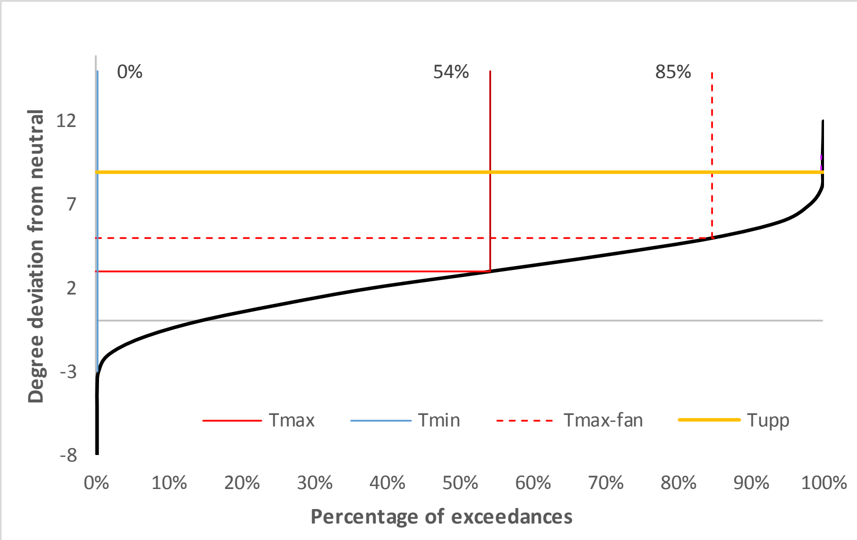
The charts in Figure 6 show the temperature time series of AKTH and FEES respectively, for the entire period of the fieldworks, bounded by upper and lower temperatures (T_{max} and T_{min}). Various other values of temperatures were displayed in the charts, external (T_{ex}), internal ($T_{ar\text{-}in}$), mean radiant (T_{mr}), running mean outdoor (T_{rm}) and fan assisted modified upper ($T_{max\text{-}fan}$). The upper limit temperature (T_{max}) as defined by the international comfort standards was found to be raised as a result of the action of the ceiling fans in the spaces by 2 °C ($T_{max\text{-}fan}$). Using the running mean temperature (T_{rm}) as an indicator, it can be seen from the charts that, for the majority of the period the T_{rm} was within the original comfort zone, in line with the adaptive thermal comfort approach (ATC) for 80% acceptability (see equations 2 and 3) (CEN 2007). However, in both spaces, the T_{rm} crossed the T_{max} in FEES theatre from March, 26 onwards and from April 02, in AKTH. However, due to the fans' action the theatres became acceptable, as can be seen from the charts that the T_{rm} did not cross the new limit ($T_{max\text{-}fan}$).

$T_{min} = 0.33T_{rm} + 15.8$ ………………………………………………….. (2)

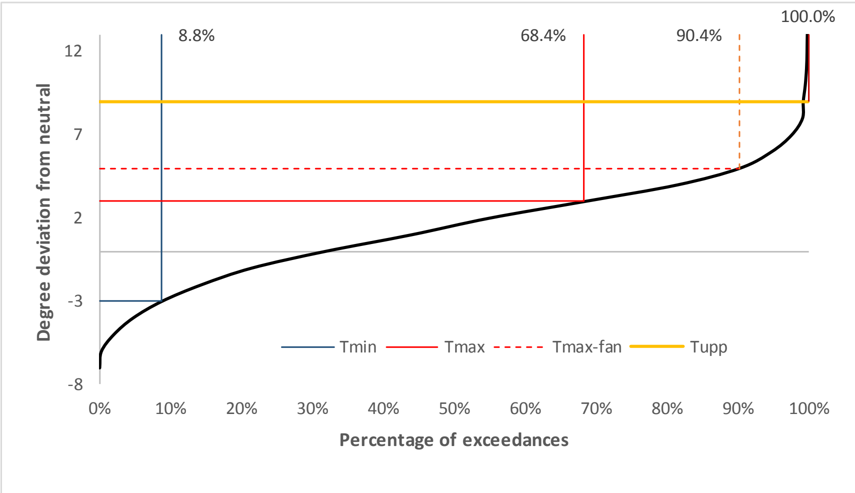
$T_{max} =0.33T_{rm} + 21.8$ ………………………………………………… (3)

Where T_{min} and T_{max} are the lower and upper ranges of allowable temperatures for 80% acceptability limits and T_{rm} is the exponentially weighted running mean outdoor temperature (CEN 2007).

The charts in figure 7 shows the percentages of exceedances (x-axis) and number of degree deviation away from the neutral temperature (y = 0) in AKTH and FEES respectively for the occupied period of the surveys. The charts indicate the percentages of time, in the theatres when the T_{max} was crossed for the entire period. The dotted and yellow lines in the charts ($T_{max\text{-}fan}$ and T_{upp}) denote the action of ceiling fans in the theatres as a result of which overheating was reduced by 31% and 22% in AKTH and FEES and reduces discomfort to 15% and 10% of the time respectively. The charts in Figure 8 however, show the percentage of degree day's exceedances the internal temperatures led to overheating, but the fans' actions reduced the discomfort to less than 5% in both spaces. This confirms that introducing the ceiling fans can improve the thermal qualities of naturally ventilated indoor spaces even in sub-Saharan Africa as opined by Nicol (2004).

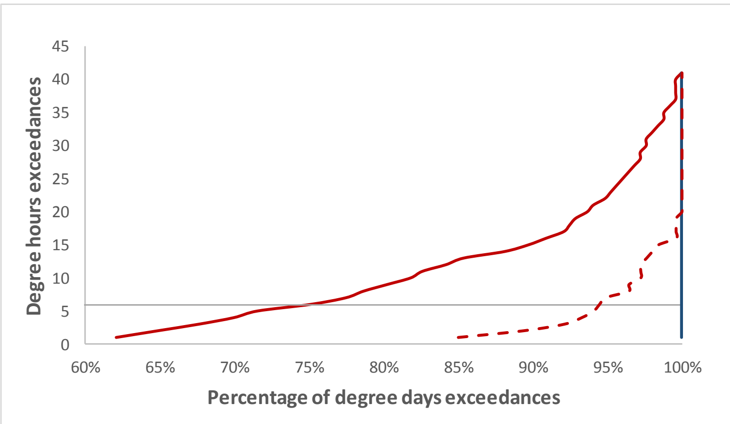


A - AKTH Theatre

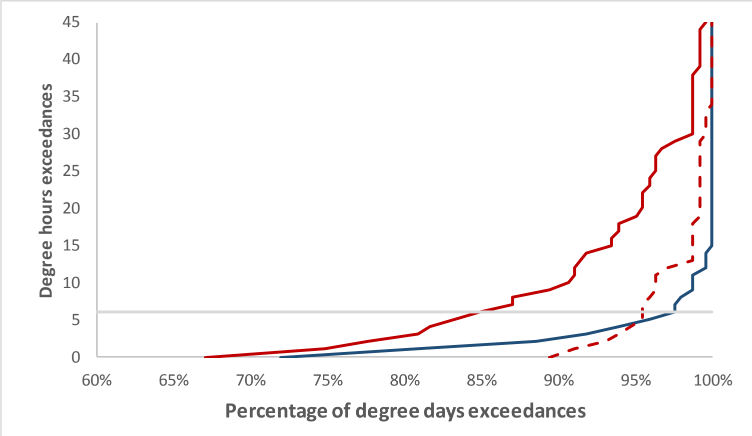


B - FEES Theatre

Figure 7: Percentage of exceedances in the theatres



A - AKTH



B - FEES

Figure 8: Percentage of degree day's exceedances in the theatres

6. Discussion

The ASHRAE Standard 55-2013, which sums up the recommendations of the major international comfort standards, specifies the values of air velocity required to compensate for elevated temperatures. The values, ranging from 0.2 m/s up to 1.2 m/s, are said to offset elevated temperatures above summer comfort threshold under occupant control up to a limit of 30 °C. The results and subsequent analysis from this study indicate that the overall thermal sensation in both theatres was warm during the summer. These conditions were indicated by PMV model, following the provisions of the thermal comfort standards such as (ISO 7730 2005). Similarly the overheating analysis from Figures 6, 7 and 8 also confirmed that the two spaces were overheated during the season, however the cooling effect brought about by the action of the ceiling fans made them acceptable to vast majority of the occupants. The increment of 2 °C in comfort temperature as a result of the elevated air speed was obtained using the ASHRAE 55 or ISO 7730 or CEN 15251 charts shown in Figure 1. It is to be noted that the highest air velocity measured during the surveys in this study was 0.65 m/s, which offset 2 °C, it therefore means that only about 1.3 °C could further be offset should the air velocity reach the allowable 1.2 m/s using the same chart.

The study found differences in magnitude in the results of AMV with those of PMV during the surveys. This is shown by correlating the differences in thermal mean votes (PMV minus AMV) against the air velocity, the regression line depicts a strong negative relationship, meaning that with an increase in air velocity the difference between the two indices reduces (see figure 9). This is in agreement with studies conducted in similar climatic regions of the world (Brager, Paliaga et al. 2004, Nicol 2004, Candido, de Dear et al. 2010, Zhai, Zhang et al. 2013). The results of the AMV during the surveys were different to those of PMV model, though the differences were not so large, it still shows that PMV/PPD model predicted a warmer perception than was found in actuality during both summer and winter, this is also in agreement with especially the adaptive thermal comfort studies around the world (Humphreys and Nicol 2002, Buratti and Ricciardi 2009, Nicol, Humphreys et al. 2012).

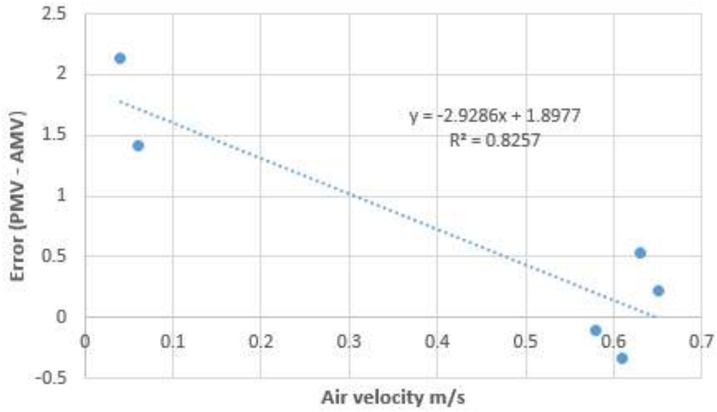


Figure 9: Air velocity versus thermal mean votes (PMV – AMV)

The summer PMV model results for the spaces (+1.56 and +2.02 for FEES and AKTH respectively) clearly show that the spaces were uncomfortably warm, while the AMV results show they were slightly warm. On the other hand, the requirements of the adaptive thermal comfort approach of CEN 15251 (2007) for buildings type II stated that the operative temperatures (T_{op}) in indoor spaces should lie within the upper and lower boundaries (T_{max} and T_{min}) of the calculated comfort range temperatures. From the same Table 6 above, it can be seen that the calculated T_{op} in the spaces across all the seasons, with exception of AKTH during the summer, fell within the said boundaries. However, when the $T_{max\text{-}fan}$ was introduced as a result of fan action, the thermal conditions in AKTH also become acceptable. The lowest boundary of the comfort range during the winter was 23.7 ˚C, while the upper boundary during the summer was 33.8 ˚C. This adequately contained the highest point reached by the T_{op} and therefore signifies that EN 15251 could therefore be used in predicting thermal conditions in Kano region.

Nevertheless, it seems that the provisions made by international comfort standards were done with less consideration of the sub-Saharan Africa in mind. For example, using these standards' recommendations, the data presented in Table 6 and Figures 6, 7 and 8 indicate that the spaces were overheated during the summer, and although the ceiling fans had greatly enhanced their thermal qualities and became acceptable to most of the occupants, the spaces still did not satisfy all the three overheating criteria recommended by CIBSE TM52. This could be explained by the fact that this comfort standard considered only the UK situations when compiling the thresholds. Similarly, one of the acceptability conditions imposed by ASHRAE 55 on prevailing mean outdoor temperature limit is a range of between 10 °C and 33.5 °C, and in this study all the mean summer temperatures recorded were found to be above this limit.

7. Conclusion

The study investigated the possibility of overheating in two lecture theatres in Bayero University, Kano, and how ceiling fans raised the levels of their thermal acceptability. Various physical parameters were measured which culminated in calculating comfort indices and concurrently the occupant were subjected to a survey to determine their actual comfort perceptions. The physical measurements and surveys were conducted from August 2016 to May 2017 and comparisons were made between the experimental and surveyed data obtained from the theatres as well as against thresholds of relevant international comfort standards. In line with the results obtained by previous thermal comfort studies, this study also found discrepancies between the measured indices and the perceived results, as well as with the comfort standards' thresholds. The PMV/PPD model overestimated the thermal perceptions of the respondents in both summer and winter. This divergence may not be unconnected with the situations of the dominant climatic conditions of the region under study, which were found to be outside the acceptability limits of the comfort standards. The theatres were found to be hot based on the results of the thermal indices recommended by the standards, however the use of ceiling fans (though operated at 0.65 m/s and below) was found to be very productive, it raised the T_{max} by 2 °C and thereby enhanced the thermal conditions of the theatres. It is however believed that higher air velocity than what this study obtained can further enhance the thermal qualities of buildings in hot and dry tropical regions, and ceiling fans can be used to achieve that.

8. References

Akande, O. K. (2010). "Passive design strategies for residential buildings in a hot dry climate in Nigeria." Eco-Architecture Iii: Harmonisation between Architecture and Nature 128: 61-71.

Al-Maiyah, S., et al. (2015). Post Occupancy Evaluation Of Daylighting And The Thermal Environment In Education Building. Passive and Low Energy Architecture (PLEA) 2015. Bologna, PLEA.

ASHRAE (2013). Thermal Environmental Conditions for Human Occupancy. Atlanta, USA, American Society of Heating, Refrigeration, and Air-conditioning Engineers, Inc. ASHRAE 55.

Aynsley, R. (2005). "Saving energy with indoor air movement." International Journal of Ventilation 4(2): 167-175.

Brager, G. S., et al. (2004). "Operable windows, personal control, and occupant comfort." ASHRAE Transactions 110(2): 17-35.

Buratti, C. and P. Ricciardi (2009). "Adaptive analysis of thermal comfort in university classrooms: correlation between experimental data and mathematical models." Building and Environment 44(4): 674-687.

Candido, C., et al. (2010). "Air movement acceptability limits and thermal comfort in Brazil's hot humid climate zone." Building and Environment 45(1): 222-229.

CEN (2007). Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels. BS EN 15251:2007.

CIBSE TM52 (2013). The Limits of Thermal Comfort: Avoiding Overheating in European Buildings 2013, Charted Institute of Building Services Engineers. TM52.

De Decker, K. (2014). "The Revenge of the Circulating Fan." Low-Tech Magazine.

Humphreys, M. A. and J. F. Nicol (2002). "The validity of ISO-PMV for predicting comfort votes in every-day thermal environments." Energy and Buildings 34(6): 667-684.

Inusa, M. and A. P. D. H. Z. Alibaba (2017). "Application of Passive Cooling Techniques in Residential Buildings: A Case Study of Northern Nigeria." International Journal of Engineering Research and Applications 07(01): 24-30.

ISO 7730 (2005). Ergonomics of the thermal environment — Analytical termination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. ISO publication. ISO 7730:2005.

Li, L., et al. (2017). "The Analysis of Outdoor Thermal Comfort in Guangzhou during Summer." Procedia Engineering 205(Supplement C): 1996-2002.

McIntyre, D. A. (1978). "Preferred air speed for comfort in warm conditions." ASHRAE Transactions 84(2): 263-277.

Mohammed, M. U., et al. (2015). "Rainfall Dynamics and Climate Change in Kano, Nigeria." Journal of Scientific Research & Reports 7(5): 386-395.

Nicol, F. (2004). "Adaptive thermal comfort standards in the hot-humid tropics." Energy and Buildings 36(7): 628-637.

Nicol, F., et al. (2012). Adaptive thermal comfort: principles and practice. Abingdon, Oxon [England], New York, NY, Earthscan.

Nicol, J. F. and M. A. Humpreys (1973). "Thermal comfort as part of a self-regulating system." Building Research and Practice 1(3): 174-179.

Schiavon, S. and A. Melikov (2008). "Energy saving and improved comfort by increasing air movement." Energy and Buildings 40(10): 1954-1960.

Sharma, M. R. and S. Ali (1986). "Tropical Summer Index - a Study of Thermal Comfort of Indian Subjects." Building and Environment 21(1): 11-24.

Tyler, H., Stefano, S., Alberto, P., Dustin, M. & Kyle, S. (2013). CBE Thermal Comfort Tool. Berkeley, Center for the Built Environment, University of California Berkeley,.

Voss, K., et al. (2013). Investigation of ceiling fans for improving summer thermal comfort.

Zhai, Y. C., et al. (2013). "Comfort under personally controlled air movement in warm and humid environments." Building and Environment 65: 109-117.

SESSION 3

Personal Control, Perception and Adaptive Behaviours

Invited Chairs:
Michael Humphreys and Madhavi Indraganti

Personal control: windows, fans, and occupant satisfaction

Margaret Pigman[1,2], Gail Brager[2], Hui Zhang[2]

[1] Resource Refocus LLC
[2] Center for the Built Environment, University of California, Berkeley

Abstract The availability of personal control is one of several explanations underlying adaptive comfort theory. This work distinguishes between four main aspects of personal control: access, satisfaction, perception, and usage. In this paper, we look at three case study mixed-mode office buildings using an expanded version of the indoor environmental quality (IEQ) survey from the Center for the Built Environment. Results reveal interesting patterns about behavior and responses to operable windows and ceiling fans, and both access to and perception of controls. For example, although the occupants were satisfied with their operable windows and fans, having access to these controls did not significantly influence their satisfaction with the indoor environment. IEQ satisfaction was most strongly correlated with perception, as measured by satisfaction with the ability to control IEQ and confidence that adjusting windows would have the desired effect.

1. Introduction

It's long been recognized that the conditions under which building occupants are thermally comfortable differ in air conditioned and naturally ventilated buildings (de Dear and Brager, 1998; McCartney and Nicol, 2002). One of the common explanations for the difference is personal control, which allows for greater degrees of behavioral adaption to achieve comfort, and shifts expectations towards a more variable thermal environment (Brager et al., 2004; de Dear and Brager, 1998; Leaman and Bordass, 2013; Paciuk, 1990). This work distinguishes between four main aspects of personal control (only the first three are addressed in this paper).

- *Access*: do you have access to a particular type of control, such as an operable window?
- *Satisfaction*: how satisfied are you with your ability to control the temperature (or air movement, air quality, etc.) in your environment?
- *Perception*: how much control do you feel like you have over the temperature (air movement, air quality, etc.) of your environment? what confidence do you have that your action will have the desired effect?
- *Usage*: how frequently do you adjust the operable windows (or ceiling fans, thermostat, etc.)?

1.1. Access to controls

Access to control is purely physical and is the easiest and most commonly recorded measure of personal control. It can be assessed objectively by a building operator or researcher – in which case it's usually at the building level. It may also be assessed at the individual level, such as in a survey, where occupants report whether they personally have access and can adjust the controls of that feature. Field studies in both naturally ventilated and air-conditioned buildings have found that occupants with access to controls such as operable windows and personal fans were more thermally comfortable than their counterparts in the same building but without the controls. We offer just a few examples here of studies that used the Center for the Built Environment (CBE) IEQ survey and database in different ways.

In a field study in a naturally ventilated office building in which some occupants had easy access to a window and others had low or no access, Brager et al. (2004) found that people with a higher level of personal control had neutral temperatures that were closer to the prevailing mean temperature, indicating that they had adapted to the conditions. Kim and de Dear (2012) found that occupants with operable windows (both in naturally ventilated and mixed-mode buildings) were significantly more satisfied with their thermal environment. Brager and Baker (2008) compared 12 mixed-mode buildings to the other 370 buildings that were in the database at the time, and found that all of the mixed-mode buildings were in the top half of the percentile ranking for temperature satisfaction.

1.2. Perceived control

Other studies have focused particularly on perceived control. Paciuk (1990) found that available, perceived, and exercised control collectively accounted for about 25% of the variance in thermal comfort. While perceived control and access to thermal controls were positively correlated with satisfaction, exercised control was negatively correlated, perhaps suggesting that a disproportionate amount of adjustment on the part of the occupants is indicative of an inherently unsatisfactory environment. She also found that the perception of control is related to but not determined by the availability of controls. Haghighat and Donnini (1999) surveyed occupants in 12 mechanically ventilated buildings and found a moderate positive correlation ($0.16 < r < 0.22$) between perceived control and overall thermal satisfaction. Langevin et al. (2012) used three of the studies in the ASHRAE RP-884 database that asked the occupants to rate their level of control over their environment. They found a statistically significant correlation between perceived control and thermal comfort votes, and a somewhat smaller but significant correlation between access to controls and thermal comfort votes. This suggests that access to controls does not fully capture the benefits of perceived control on thermal comfort.

Boerstra et al. (2013a) used general survey data from 64 European office buildings, evaluating control only at the building level, and found significant correlations between perceived control over temperature and thermal comfort in the winter, but not the summer. However, they did not find a significant difference in perceived control over temperature when comparing occupants in buildings with and without operable windows, suggesting that mere availability of windows does not necessarily translate into occupants feeling like they can effectively influence the temperature. Yet in another study (Boerstra et al., 2013b), using responses of 326 occupants in 9 Dutch office buildings and considering access to controls at the occupant rather than building level, they found that access to operable windows and adjustable thermostats significantly increased occupants' perceived control over their environment.

Studies looking at the effects of control on thermal comfort have varied in both their methods and their conclusions. Although personal control is an important component of the adaptive hypothesis, there have been limited studies that have addressed the impact of access to personal controls on satisfaction with IEQ. And there have been even fewer studies that have addressed the more complex ideas of perceived control, or satisfaction with the effectiveness of control, as a central component of their hypotheses or methods. This paper is just one step in trying to address this gap.

1.3. Objectives

We used results from the CBE IEQ survey in three mixed-mode case study buildings that were designed to be high-performing to investigate: 1) user behavior and satisfaction with operable windows and fans, and 2) the effects of various metrics related to personal controls on satisfaction with IEQ parameters.

2. Methods

2.1. CBE IEQ survey

This study used a web-based IEQ survey, first developed by CBE in 2000. In addition to basic questions about demographics and workspace descriptions, the core CBE survey measures occupant satisfaction and self-reported productivity related to nine environmental categories: office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, cleanliness and maintenance, overall satisfaction with the building, and with the workspace. We also used additional CBE survey modules that focused on behavior patterns and responses related to operable windows and fans. In addition to satisfaction with a particular IEQ attribute, the survey also asked about satisfaction with one's ability to control that attribute. Satisfaction questions use a consistent 7-point scale that ranged from -3 (Very dissatisfied) to 0 (Neutral) to +3 (Very satisfied). When occupants are dissatisfied with an element of the environmental quality of their workplace, they see additional "branching" questions to probe the reasons for their dissatisfaction.

To assess the various characteristics of personal control described earlier, we used the following survey questions:

- *Access*: Which of the following do you personally adjust or control in your workspace? (response: checklist of features including windows, fans, etc.)
- *Satisfaction*: How satisfied are you with your ability to control the temperature in your workspace? (response: 7-point satisfaction scale)
- *Perception*: When you open the window, what confidence do you have that your action will have the desired effect? (response: 7-point scale from "unsure" to "very sure")
- *Usage*: How often do you typically adjust your windows in the warm/hot season? (response: daily, weekly, monthly, less than once a month, never)

2.2. Description of case study buildings

The three case study buildings considered in this paper are all designed to be high performance (in terms of energy-efficiency, and other attributes as described by their LEED Gold or Platinum ratings), are mixed mode, and are in different climate zones of the United States.

Building A is a LEED Gold building with both offices and laboratories, and is located in a temperate marine climate of the Pacific Northwest, where the average summer highs are around 24°C. It has ceiling fans in addition to operable windows and is operated with temperature set points of 20–22°C in the offices and 20-21°C in the laboratories. The upper windows are automatically controlled, while the lower ones are manually controlled by the occupants.

Building B is a LEED Platinum office building located in a dry mountainous continental climate with average summer highs around 28°C. Its relatively narrow floor plate (18 m wide) allows all workstations to be located within 9 m of a window for daylighting, natural ventilation, and views to the outside. Slightly more than half of the windows are manually operated with the Building Management System providing suggestions about when to open and close them, and the rest are fully automated. When required, the building is mechanically cooled with radiant and evaporative cooling. The CBE survey was administered in this building both before and after stochastic optimization of the building control logic (referred to later as pre- and post-intervention).

Building C is a LEED Platinum building located in a hot/dry desert climate of the Southwest, with average summer highs around 40°C. It is a net zero energy office building and has ceiling fans in addition to operable windows. Four shower towers (i.e., evaporative coolers) and a solar chimney cool the building passively so that the mechanical cooling only turns on above 28°C.

3. Results

This section is organized by first looking at general patterns of satisfaction with IEQ parameters and the ability to control them. We then look at responses and behavior patterns related to windows and fans in particular. And finally, we explore in more detail the role of actual and perceived control on those satisfaction patterns. It should be noted that when assessing "acceptability", we followed the ASHRAE Standard 55 guidelines of defining acceptability as votes ≥0 on the 7-point satisfaction scale (i.e., grouping "neutral" votes with "satisfied" ones) (ANSI/ASHRAE, 2013).

3.1. Satisfaction with IEQ parameters and ability to control them

In the three buildings (four surveys), there were a total of 180 responses. As a testament to these being well-liked by the occupants, 100% were satisfied with their building overall (Table 1). When we look at thermal satisfaction, however, the 80% acceptability target of ASHRAE Standard 55 was achieved only in the post-intervention survey in Building B, and in Building C. This is a common pattern, however, where we are seeing that most buildings in the CBE database fall short of ASHRAE's 80% acceptability goal (Karmann et al., 2017). Nonetheless, all three of these buildings were still performing better than most in the CBE benchmarking database, particularly Building B (post-intervention) and Building C, as indicated in the "CBE percentile scores" in Table 1.

Table 1. Basic survey results for three buildings.

Number of responses (rate)		Building A 41 (35%)	Bldg B, pre 62 (60%)	Bldg B, post 40 (38%)	Building C 37 (82%)
Satisfaction with:					
Building overall	Mean vote	2.03	NA	2.45	2.19
	% acceptability	100%		100%	100%
	CBE percentile	90%		99%	95%
Thermal comfort	Mean vote	0.38	0.95	1.18	0.97
	% acceptability	60%	75%	85%	81%
	CBE percentile	70%		95%	91%

For reference, we also compared the building overall and thermal comfort mean scores to other past studies that administered the CBE Survey in buildings with operable windows (Table 2). The overall building satisfaction was substantially higher than in any of these other studies, again indicating that these buildings were very positively perceived by the occupants. In terms of thermal comfort, there were more mixed results. While the mean thermal satisfaction scores in these three buildings were substantially higher than those found in the larger CBE database, Building A had the relatively lowest satisfaction among the three, and the potential reasons for this and implications for designers and building operators will be explored further. The buildings were perceived as more thermally comfortable than the other naturally ventilated and mixed-mode buildings in the U.S.; in contrast, we saw higher levels of thermal satisfaction in 12 buildings in India that had operable windows and fans, which could be an interesting testament to cultural differences, as well as adaption to both the climate and to the more common practice in India of using windows and fans for comfort control.

Table 2. Comparison of thermal satisfaction survey results for three buildings and other studies.

	Current study				Past studies				
	A	B, pre	B, post	C	CBE Benchmark	MM U.S.[1]	MM India[2]	NV, Berkeley warm season[3]	NV, Berkeley cool season[3]
Number of responses:	41	62	40	37	714	520	470	98	95
Satis' with:									
Building overall	2.03	NA	2.45	2.19	1.11	1.80	1.83	1.49	1.51
Thermal comfort	0.38	0.95	1.18	0.97	0.09	0.81	1.36	0.88	0.87

Note: CBE Benchmark represents both naturally ventilated (NV) and air-conditioned buildings. MM refers to Mixed Mode. Sources: 1-(Brager & Baker 2008). 2-(Brager et al 2017); 3-(Brager et al 2004).

Figure 1 shows a summary of the satisfaction responses with selected IEQ parameters (air quality, air movement, and temperature) and control over these parameters for the three buildings. Overall building satisfaction has the most favorable ratings while temperature control has the least (especially in Building A). Air movement control in Building C was also relatively low. The differences between buildings in satisfaction with air movement, air movement control, and temperature control are statistically significant ($p < 0.05$).

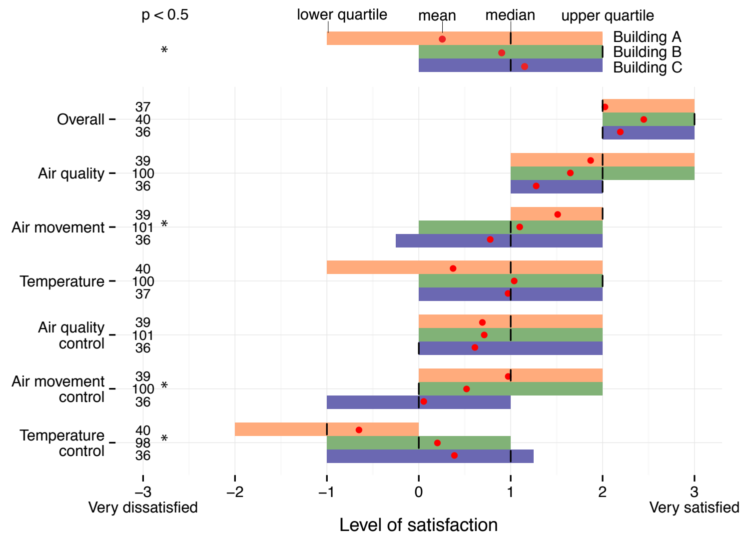


Figure 1. Satisfaction levels by building

NOTE: The two surveys from Building B are combined in this figure. The numbers on the y-axis represent sample size for that question in each building

Although we recognize that the sample sizes in these buildings are insufficient to allow us to generalize, we can still identify trends in building design and operation that can impact comfort. Let's take Building A in the Pacific Northwest as an example. Figure 1 shows that Building A was noticeably worse than the other two in terms of both satisfaction with temperature, and with *control* of temperature, and responses to these two questions was also quite different. Approximately twice as many people were satisfied with the temperature than were satisfied with their ability to control it. This is perhaps not surprising given that being too cold is overwhelmingly the problem (see Figure 2 below). Yet, the types of control available to them (window blinds/shades and ceiling fans) are not going to help them at all become warmer. Also, almost half of the respondents don't have any control of their indoor environment (Figure 9, discussed later). This begins to suggest that simply having some form of environmental control isn't necessarily helpful unless there is a clear match between the *type* of control and the likely *source* of thermal discomfort.

3.2. Reasons for dissatisfaction with temperature

The people who expressed dissatisfaction with a particular attribute were presented an additional question with a list of potential sources of dissatisfaction, and were asked to check all that apply. Note that some of the questions specifically asked them to reflect on conditions in warm vs. cool weather. There were distinct differences in the complaints between the three buildings (Figure 2), which again points to their unique circumstances and design characteristics that we can learn from. In Building A, for the 21 people (out of 41 surveyed) expressing dissatisfaction with temperature, the complaints were overwhelmingly of being too cold, whether it was their hands, their feet, or their workspace. We were surprised to see that these patterns occurred in both warm and cool weather, and upon further investigation discovered that the temperature setpoints in this building were 20-22°C year-round, which is at the lower end of the winter temperatures recommended by ASHRAE. This operational strategy was not only making people uncomfortable, but it does not take advantage of the low-energy features of the design, such as operable windows and ceiling fans, which are best at providing comfort at the warmer range of comfort. It's also interesting to note that, in this building, whether or not the respondent had access to a personal control did not make any appreciable differences in the *reasons* for dissatisfaction with temperature – which makes sense given that the controls that were available wouldn't have been effective at overcoming the reason for feeling cold. These findings suggest that a simple operational change of increasing the temperature setpoints a small amount in the winter could improve comfort, while a larger increase in the summer, combined with encouraging the use of windows and fans, could improve both comfort and energy performance.

In Building B, there was a smaller proportion (16 people out of 102 surveyed) who expressed dissatisfaction with temperature, and for them the most common complaint was that the air movement was too low. As with Building A, there weren't any differences in whether the people who expressed this complaint had access to controls or not, since fans simply weren't available to improve these conditions. It's particularly interesting to note that this was not a problem in either of the other buildings where ceiling fans were installed, so this suggests a fairly obvious easy fix.

Building C was in the hottest climate of the three. Among the 7 people (out of 37 surveyed) who were dissatisfied with the temperature, most complaints were about being too hot or that the air movement was too high. Since the summer setpoint is 28°C, the occupants rely on the fans to provide a cooling effect, but some people complained that they blow dust and papers around.

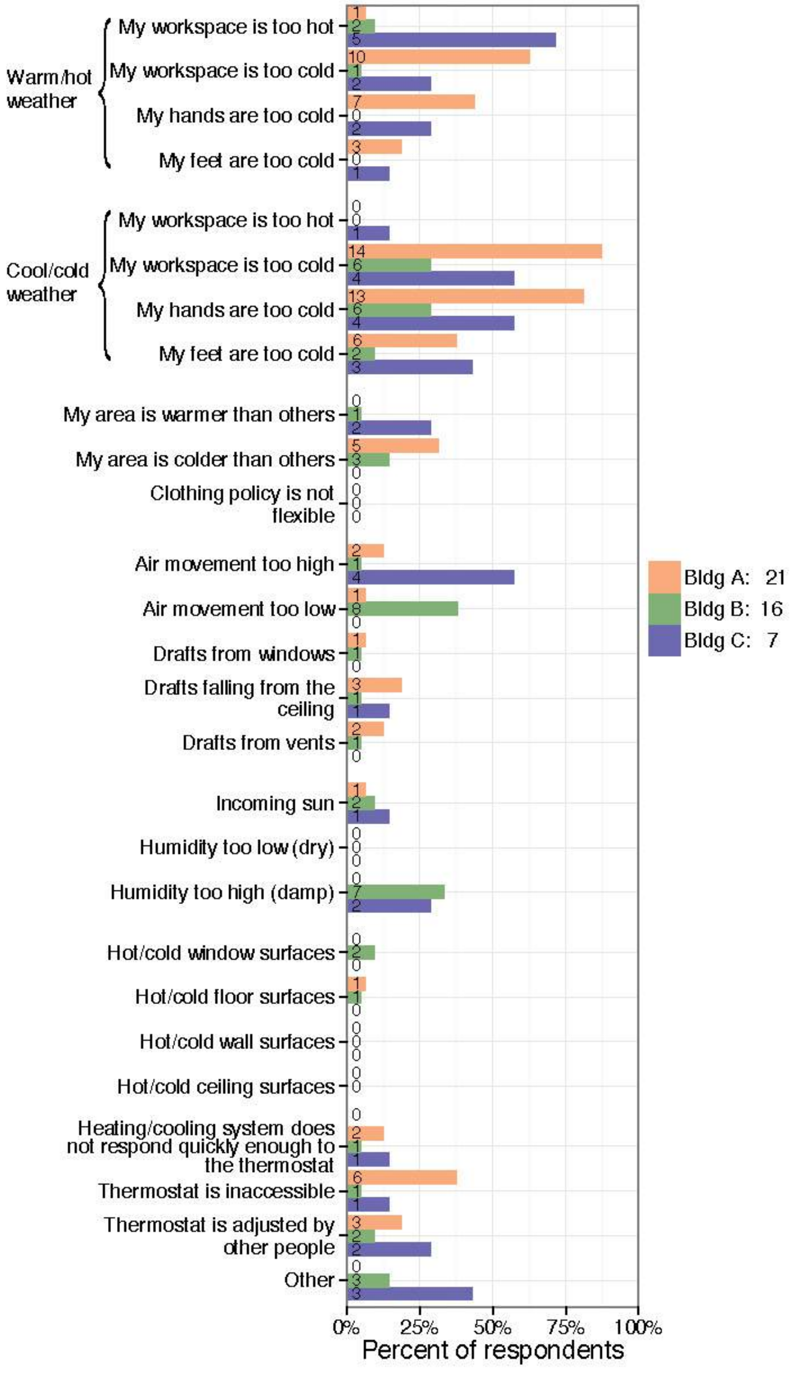


Figure 2. Reasons for temperature dissatisfaction by building

3.3. Windows

3.3.1. Satisfaction with operable windows

The respondents were very satisfied with the operable windows—only 4% were dissatisfied with a mean satisfaction score of 1.5, which falls between "slightly satisfied" and "satisfied" on the scale used (**Error! Reference source not found.**3).

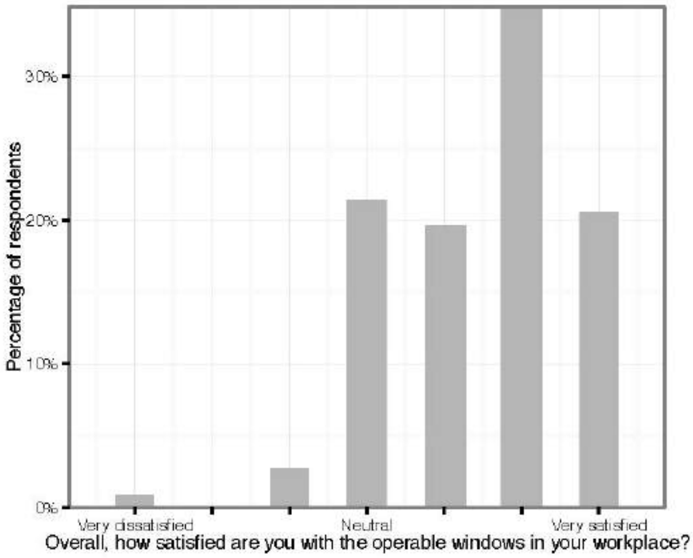
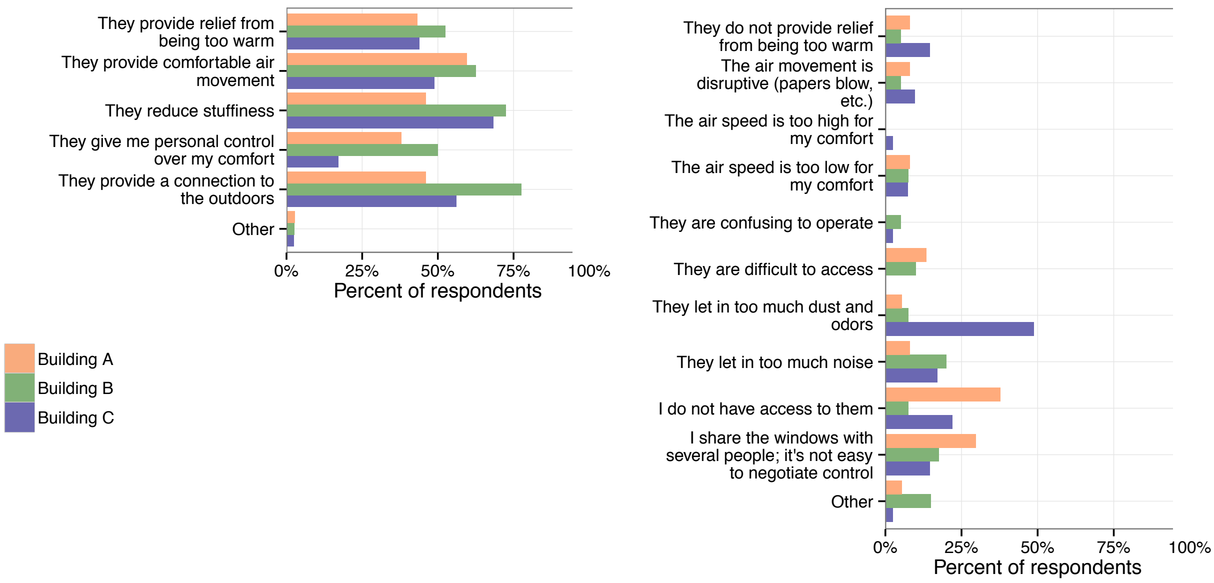


Figure 3. Satisfaction with operable windows

The surveys listed possible reasons for being both satisfied and dissatisfied with operable windows and asked the respondents to indicate the ones they agree with. The reasons for satisfaction related to thermal comfort, air quality, and connection to the outdoors had similar rates of agreement, while access to personal control was the least common response in all three buildings, particularly in Building C, which was in the hottest climate (Figure 4a). It's interesting to note that while people recognized that the windows were impacting the thermal conditions (relief from being too warm, providing air movement), they were not necessarily associating that with the phrase "personal control", which could simply be a reflection of their understanding of the terminology.



a. Reasons for satisfaction b. Reasons for dissatisfaction

Figure 4. Reasons for satisfaction and dissatisfaction with operable windows

Noting that there was a very small percent of people who were dissatisfied with the operable windows, for those that were - some of the main reasons there were dissatisfied were related to a scarcity of windows (i.e., people complained about not having access to windows or about having to share windows with too many people). Noise was another of the most common complaints; but even then, only about 20% of the small number of dissatisfied occupants in each building listed it as a problem. At Building C, dust and odors were also mentioned as a problem, again perhaps reflective of the hot-dry climate of that location (Figure 4b).

3.3.2. Reasons for adjusting windows

The survey asked separate questions about why the respondents both open and close windows to control their thermal environment, and the results are shown below in Figure 5. Note that some of the potential reasons were only given for one of the "why open" or "why close" questions, and hence there are not necessarily two colored bars for each option.

In terms of wanting to feel warmer or cooler (the top two choices), occupants clearly opened the windows to feel cooler (73%), but the reasons for closing the windows included feeling both cooler (41%) and warmer (61%). This is likely a reflection of the status of interior air conditioning and heating relative to the outside climate. Windows are also an important way of controlling air movement: 70% of the respondents opened windows to increase air movement and 20% closed them to decrease air movement.

But the windows were used not just for thermal comfort—95% of the respondents adjusted their windows for at least one reason other than thermal control and 70% for at least four reasons. The single most frequently cited reason for opening windows was for fresh air (91%). Other non-thermal reasons include controlling dust, smells, and other pollutants as well as sounds, conserving energy, and responding to coworkers' and management's requests. There results were all fairly comparable to those found in Brager et al (2004).

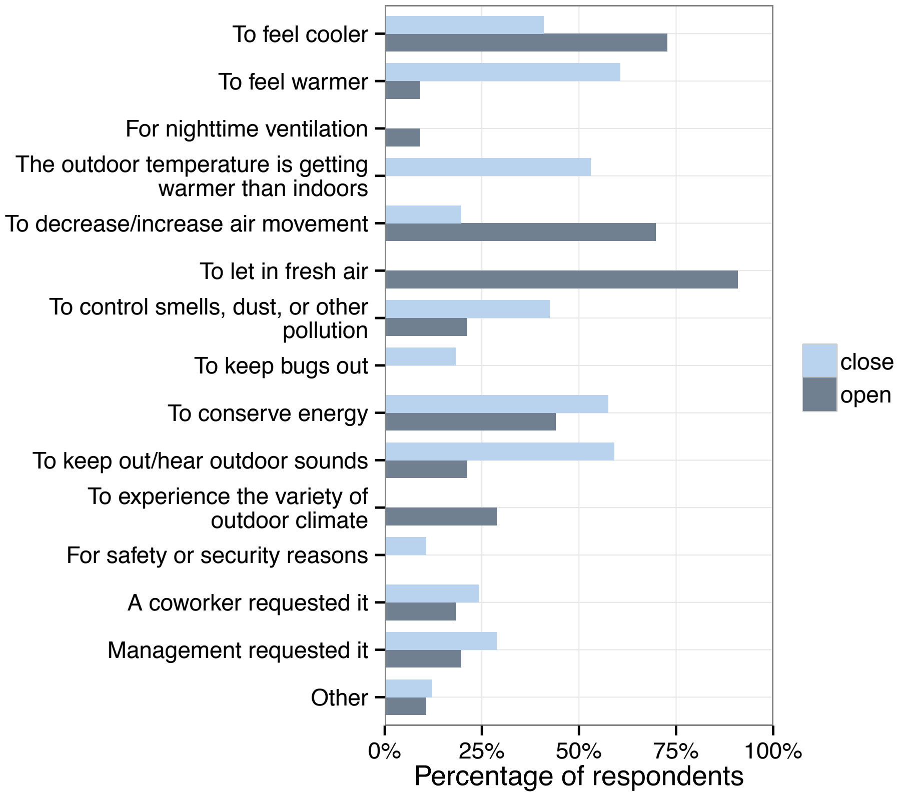


Figure 5. Reasons for opening and closing windows

3.4. Fans

3.4.1. Satisfaction with ceiling fans

Although all three buildings had operable windows, only two of them had ceiling fans (Buildings A and C), and the percent of people satisfied with the fans in these two were very high, but slightly less than the responses for the windows —only 8% were dissatisfied and the average score was 0.95, "slightly satisfied" (Figure 6). It was interesting to compare this to the 12 mixed-mode buildings in India with operable windows, where slightly higher (11%) were dissatisfied, but the average score was also higher (1.32) (Brager et al., 2017). This is because there were a very large number of people in the U.S. buildings who voted neutral, while in India there was a much larger number who were distinctly satisfied (a vote of 2 received the overwhelming largest proportion of votes). This could be a reflection of the Indian culture being more accustomed to fans, compared to a large number of the occupants of the U.S. buildings not having an opinion either way.

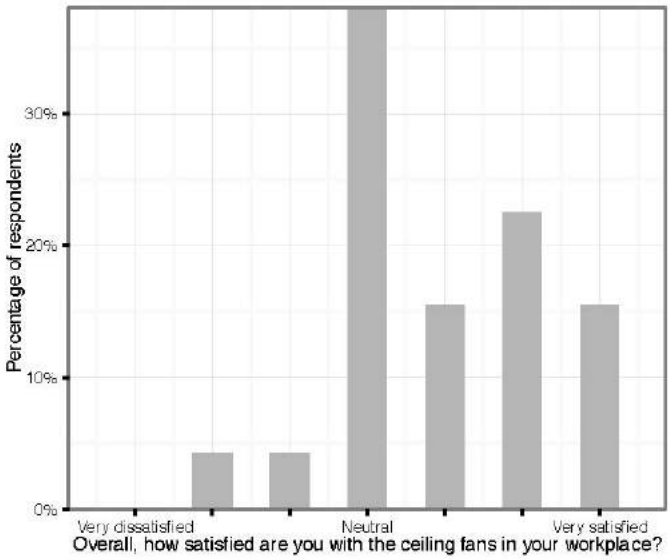
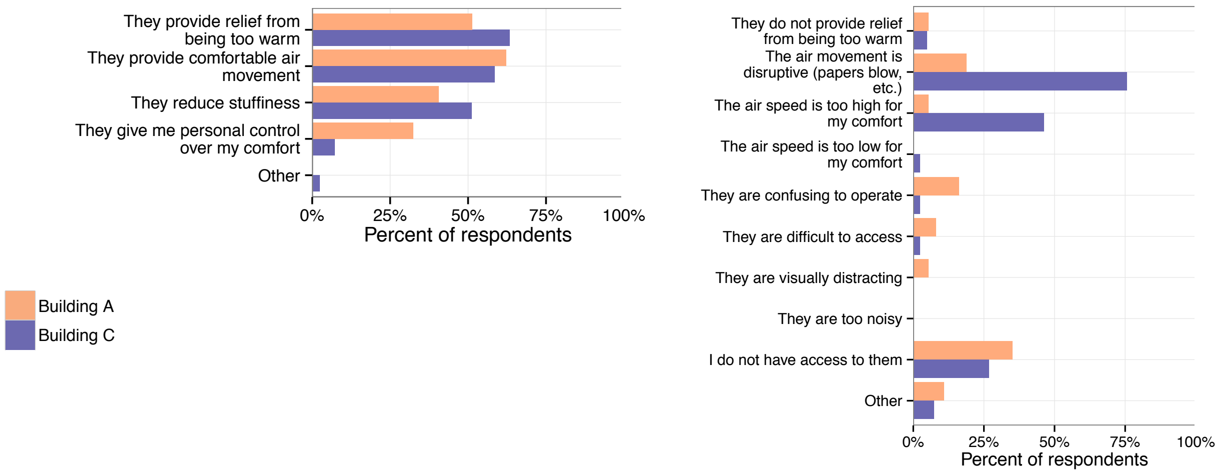


Figure 6. Satisfaction with ceiling fans

As with the windows, the survey listed possible reasons for being both satisfied and dissatisfied with ceiling fans and asked the respondents to indicate the ones they agree with (Figure 7). Close to 50% of people were satisfied with ceiling fans for each of the 3 possible reasons related to thermal comfort and air quality. It's interesting that while fans don't have any effect on the actual pollutant levels in the air, the air movement has a noticeable effect on perceived "stuffiness", which is clearly a perception rather than a measure of actual air quality.

Like with windows, the least common reason for being satisfied with fans in both buildings was that they give personal control (Figure 7a). Surprisingly, significantly more respondents in Building A were satisfied with fans for the personal control compared to Building C, despite the earlier finding that occupants of Building A were frequently too cold. In Building C, where people were more likely to be too warm, very few respondents reported that fans give them personal control over their comfort. This is likely due to that fact that most of the fans in Building C are set automatically, and points to the potential impacts of a social dynamic where only one or two people control the fans for the whole office.

In terms of dissatisfaction, the main complaints at Building C were related to the air movement being too high—for comfort and because of blowing papers. Otherwise, like for windows, the most common complaint was not having access to control of fans. No one complained that the fans were too noisy (Figure 7b).



a. Reasons for satisfaction b. Reasons for dissatisfaction

Figure 7. Reasons for satisfaction and dissatisfaction with fans

3.4.2. Reasons for adjusting ceiling fans

Again noting that there was a very small percent of people who were dissatisfied with the fans, only nine occupants responded to the questions about why they turned their fans on and off, and all nine were in Building A; though the Building C also had fans, they were set automatically. Given the small number, we are intentionally presenting the results below as numbers rather than percent (Figure 8). Of the people who responded, they consistently used their fans for thermal comfort, air movement, and air quality (i.e., stuffiness) reasons, and the least frequent reasons cited (for turning fans off) were to reduce noise and to conserve energy (Figure 8).

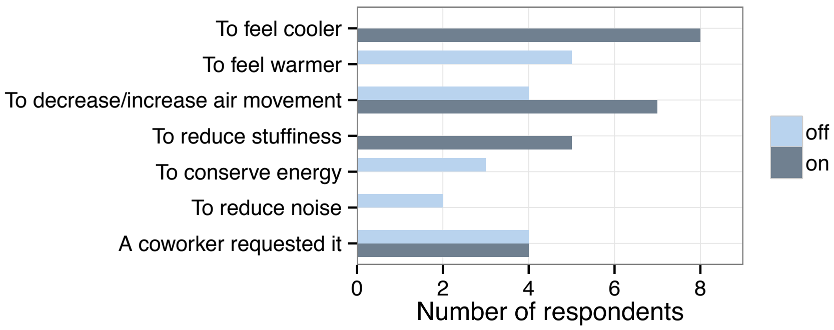


Figure 8. Reasons for turning fans on and off—Building A only

3.5. Personal controls

While it's clear that people were satisfied with the windows and fans, these were not the only forms of personal control in these buildings. And the previous results also suggested that while people enjoyed using them, they didn't always associate these devices with the idea of "personal control". So, we turn now to investigating the notion of personal control in a bit more detail, using the framework described in our introduction, distinguishing between satisfaction, access and perception.

3.5.1. Satisfaction with IEQ and with IEQ control

Using occupants' subjective responses from the survey, satisfaction with IEQ and satisfaction with *control* of IEQ parameters are strongly correlated, particularly for air movement and temperature, as summarized in Table 3. Interestingly, satisfaction with the ability to control one parameter is correlated with satisfaction with *all* of the IEQ parameters noted in the table, not just the one that is being controlled.

While these findings do not in themselves prove causality, it might suggest that if people are satisfied with having a degree of control, they may be more satisfied not only with the attribute they are controlling, but perhaps other environmental factors as well. On the other hand, maybe the effect might be working in the other direction. If they're happy with an attribute, then they're satisfied with the level of control in general since they're already comfortable.

Table 3. Squared correlations between satisfaction with thermal parameters and satisfaction with the ability to control them

	air movement	air quality	temperature	overall
air movement control	0.49	0.21	0.18	0.11
air quality control	0.31	0.33	0.2	0.18
temperature control	0.19	0.13	0.51	0.13

This finding is slightly different from, but still has some similarities with, findings by Brager et al. (2004), where occupants in a naturally ventilated building were divided into groups with direct control of windows, and those without control (note that this was based on people's relative access to windows, not satisfaction with control, as analyzed above). Although physical measurements verified that these groups were exposed to comparable environmental conditions, the group with a higher degree of control were more satisfied with every aspect of their environment.

3.5.2. Access to controls

The previous results were based exclusively on satisfaction scores in the survey. We next look at what features of the building give occupants some degree of personal control.

Access to personal control, as reported by the occupants, varied widely between the three buildings. The survey presented a list of potential building features, and respondents checked which ones they had access to (Figure 9). Almost 80% of the respondents in Building C checked "none of the above", implying that they did not have access to any controls, while only 39% and 33% similarly had no access to controls in Buildings A and B, respectively.

The most common type of control in Building A was window blinds or shades (41%), followed by ceiling fans (22%). Overall, 54% of the respondents from Building B had access to operable windows, which is surprisingly low given the narrow floorplate. However, even with a narrow floorplate, if there is another workstation between the occupant and a window 5 meters away, that occupant is likely to report that they don't have access. This suggests that an individual's sense of "access" is very personal and not necessarily a reflection of the building design. For the 20% of occupants in Building C who reported access to at least one listed item, responses were distributed and there was no singular common control feature.

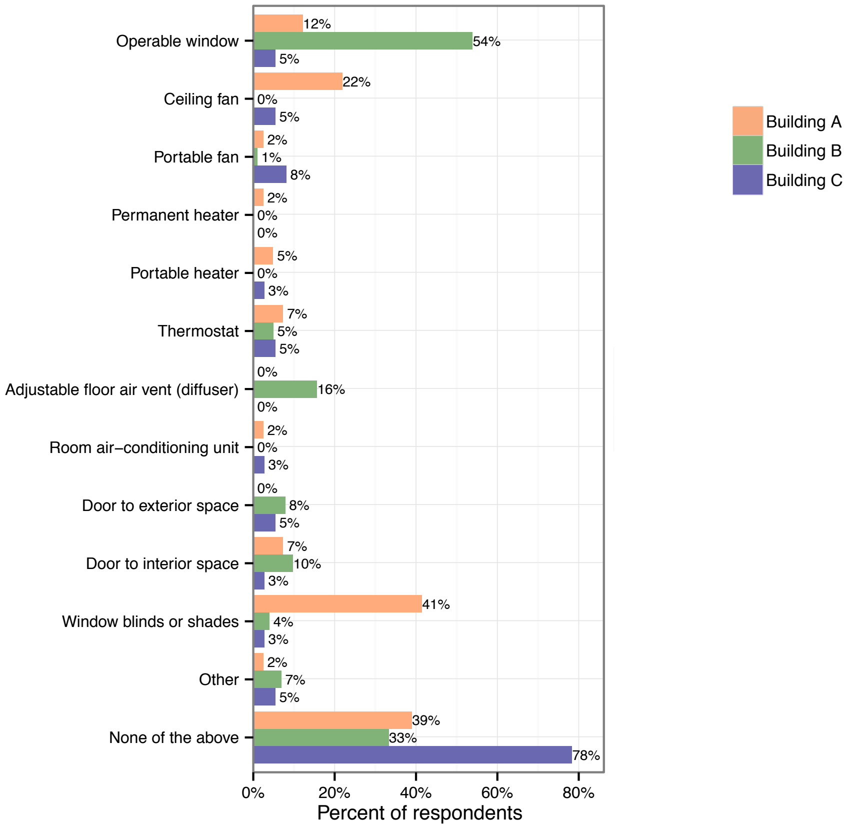


Figure 9. Personal controls available by building, as reported by survey respondents

3.5.3. Access to controls and satisfaction

We now want to connect the occupants' access to control features and their subjective assessments of satisfaction. In other words, to what extent is access to personal control associated with satisfaction with 1) IEQ parameters and 2) control of those parameters?

One challenge is how to statistically explore this while controlling for differences that could be attributed to other characteristics of each building (i.e., if people in one building might be more satisfied overall, regardless of access to controls). To address this, we conducted linear regressions between the satisfaction metrics and access to the various control features noted above, while partialling out the building. The form of the equation for evaluating the effects of personal controls is:

$$satisfaction = b_1 * control + b_2 * building + b_0 \qquad \text{Equation (1)}$$

In Equation 1, "Satisfaction" can refer to either the IEQ attribute, or control of that attribute. "Control" refers to the feature they have access to, such as windows, fan, thermostats, etc. Note that regressions were run only for control features that have at least ten individuals. Only the partial regression coefficients, b_1, that achieved significance ($p < 0.1$) are shown in Table 4 (i.e., only for the attributes of satisfaction with control of air quality, control of air movement, and daylight for Bldg A - but it should be noted that this was the only building in which the question was asked specifically about daylighting, whereas the other buildings had questions about lighting in general). For these, all of the statistically significant coefficients were positive, indicating that having access to that control feature increases satisfaction. The blank rows are intentional, to show what regressions were run (i.e., more than 10 individuals in a group), but produced no statistically significant findings. The "access to any control" refers to a group of people who had access to at least one feature (i.e., everyone except "none of the above" as listed in Figure 9

Table 4. Partial regression coefficients of personal controls predicting satisfaction (b_1). Only statistically significant ones are shown. Blank cells indicate that regressions were run with no statistically significant results.

Satisfaction with:	Access to operable window	Access to blinds	Access to any control
Air quality			
Air quality control	0.95 ***		0.47 •
Air movement			
Air movement control	0.72 *	0.99 *	0.50 •
Temperature			
Temperature control			
Daylight (Bldg A only)		1.2 •	
Glare (Bldg A only)			

NOTE: significance codes • p < 0.1; * p < 0.05; ** p < 0.01; *** p < 0.001

Based on this analysis in the three buildings being studied, we see that *access* to controls is not correlated with satisfaction with any of the IEQ attributes themselves. However, there are some limited correlations between access to controls and satisfaction with *controlling* IEQ attributes, but not as much as we would have expected. Access to an operable window is associated with increased satisfaction with *control* of air quality and *control* of air movement, but it was not associated with satisfaction with temperature, or *control* of temperature. Even in the cases shown here where access to control is statistically significant, the effect size is very small—R^2 is 0.02-0.07. This suggests that, for these three buildings, one's *satisfaction* with control (Section 3.5.1) seems to be more important than simply having *access* to personal controls.

3.5.4. Perceived control and satisfaction

Another subjective indicator, as described in the introduction, is the notion of *perceived* control. Using the CBE survey, we represented this by the *confidence* people had that their action would have the desired effect. Returning to our focus on operable windows, there were strong correlations between satisfaction with *control* of IEQ parameters in these buildings and the *confidence* that adjusting a window will have the desired effect. Closing confidence (i.e., confidence that closing a window will have the desired effect) is correlated with satisfaction with all three types of control – temperature, air movement, and air quality (R^2=0.21-0.27), while opening confidence is only correlated with temperature control satisfaction (R^2=0.13). While interesting, these results should be treated with caution because only 40% of the respondents answered the questions. Boerstra et al. (2013a, 2013b) has done a much more extensive study focused on perceived control, and field study results showed that: 1) frequency of use of controls was linked to perceived control, 2) access to operable windows (as well as not having policies that prohibit use of windows and thermostats) can have a positive and significant effect on perceived control, and 3) there were positive and significant associations between perceived controls and comfort and overall satisfaction. But more work is needed in this area.

4. Discussion

Consistent with what we've found in most buildings in the CBE IEQ survey database, the respondents from the three case study buildings were more satisfied with the building overall than with the temperature per se. This speaks to the fact that thermal comfort is only a small component of the experience of a building, and one can never know what range of factors an individual is considering when answering the question "*how satisfied are you with the building overall*?" But it also suggests that even our beloved, high-performance buildings aren't necessarily creating high-quality indoor environments and designers need to pay more attention to such details.

In these three buildings, there was a high level of satisfaction with the operable windows, and good but slightly lower satisfaction with the fans. The most common reason that the respondents gave for opening their windows was to let in fresh air. Thermal comfort issues (temperature and air movement control) were the next most common reasons, but 95% of the respondents reported adjusting their windows for at least one non-thermal reason. This finding can also help us understand why there was a high level of satisfaction with the windows, but not a strong correlation between having windows and being satisfied with the thermal conditions. This implies that building owners shouldn't use the potential for natural ventilation and cooling as the sole reason for deciding whether to put in operable vs. fixed windows.

In practice, common barriers to installing operable windows include concerns about outside noise and increased dust and odors. In the case study buildings, less than 25% of the only 4% of respondents who reported that they were dissatisfied with the windows noted that it was because of noise. This is consistent with previous findings that complaints about indoor noise are about ten times more prevalent than complaints about outdoor noise (Goins et al., 2012). Potential complaints about dust and odors are likely to be very site dependent.

Beyond specific responses about windows and fans, this study found no correlation between having *access* to controls, and satisfaction with IEQ, and only limited correlation between access and satisfaction with *control* of IEQ – specifically air movement and air quality, but not temperature. We have shown that the simple fact of having *access* to a window is not, by itself, a good predictor of satisfaction, but the occupants' feelings about its effectiveness is. While these results were initially surprising and disappointing, we believe this might speak to the difference between *available* controls and the *perception* of control, as alluded to by others in the literature (Langevin et al., 2012; Paciuk, 1990, Boerstra et al., 2013a, 2013b), and also to the importance of context. For example, the available controls in each of these particular buildings may have been irrelevant for the most common problems that occurred in each. This appears to be the case at Building A, where the dominant complaint was being too cold and the most common controls were curtains/blinds and ceiling fans. If the operations of the building changed from the current conditions of overcooling, to maintaining conditions within the warmer side of the comfort zone, we might see improvements in comfort and the effectiveness of personal controls, as well as energy use.

Satisfaction with your *ability* to control something may be associated with your perceived *need* for that control. For example, if people are already comfortable most or all of the time, they might be very happy with their "ability to control temperature" even if they don't actually have *access* to any controls (i.e., one isn't likely to be frustrated with lacking something that they don't feel they need in the first place). Or someone might have physical access to a window but perceive that they have *no* "ability to control temperature" because the window will just let in cold air, and they are already uncomfortably cold (i.e., you may have a need, but the type of control you have isn't going to help).

It is tempting to think that satisfaction with the ability to control something causes satisfaction with that thing, but the causality could easily go the other direction. Correlation does not imply causation and it certainly doesn't indicate which is the cause and which is the effect. And while it is indeed compelling to researchers to try to demonstrate causality between personal control and satisfaction, we are still far from being able to establish this.

5. Conclusion

To investigate people's behavior and responses to windows and fans, and the effects of personal control on their overall satisfaction with IEQ, we considered three mixed-mode buildings in which the CBE IEQ survey had been administered.

From these surveys, it is clear that the occupants really appreciate their windows and fans, and these should be considered worthwhile components of office buildings. We found that satisfaction with the IEQ parameters was not significantly related to simply having *access* to personal controls. Based on the correlations, satisfaction with IEQ was most strongly associated with *perceived* control, as represented by one's confidence that adjusting windows would have the desired effect, and by satisfaction with the *ability to control* the IEQ parameters. These results emphasize the importance of people's perception of how effective the controls actually are, rather than just simply having them. This suggests that it is important to go beyond simply putting personal controls in place, and to also educate the occupants to help them understand how to use them, and increase their awareness of the effect they will have.

More research is clearly needed to better understand the relationship between occupant experience and available vs. perceived control. The adaptive hypothesis rests, in part, on the idea that personal control influences thermal comfort, but simple access to controls is not enough. For designers to be able to take full advantage of adaptive principles, they need to know what is required to enable occupants to perceive that the control they have over their thermal environments will actually be effective.

6. Acknowledgements

This project was supported by funding from the California Energy Commission project 500-10-025, Natural ventilation for energy saving in California commercial buildings and ASHRAE URP-1656, Development of ASHRAE database II.

7. Bibliography

ANSI/ASHRAE, 2013. Standard 55: Thermal environmental conditions for human occupancy.

Boerstra, A., Beuker, T., Loomans, M., Hensen, J., 2013a. Impact of available and perceived control on comfort and health in European offices. Architectural Science Review 56, 30–41. doi:10.1080/00038628.2012.744298

Boerstra, A., Loomans, M., Hensen, J., 2013b. Personal control over temperature in winter in Dutch office buildings. HVAC&R Research 19, 1033–1050. doi:10.1080/10789669.2013.843961

Brager, G.S., Baker, L., 2008. Occupant satisfaction in mixed-mode buildings, in: Air Conditioning and the Low Carbon Cooling Challenge. Presented at the Windsor, Network for comfort and energy use in buildings, Windsor, UK.

Brager, G.S., Paliaga, G., de Dear, R., 2004. Operable windows, personal control, and occupant comfort. ASHRAE Transactions 110, 17–35.

Brager, G., Manu, S., Pittman, M., 2017. Summary of survey results: 12 Mixed Mode buildings in India. Internal Report, CBERD Project, Center for the Built Environment, UC Berkeley.

de Dear, R., Brager, G., 1998. Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions 104, 145–167.

de Dear, R.J., 1998. A global database of thermal comfort field experiments. ASHRAE Transactions 104, 1141–1152.

Goins, J., Chun, C., Zhang, H., 2012. User perspectives on outdoor noise in open-plan offices with operable windows. Architectural Science Review 56, 42–47. doi:10.1080/00038628.2012.745390

Karmann, C., Schiavon S., Graham, L., Raftery, P., Bauman, F. 2017. Comparing Temperature and Acoustic Satisfaction in 60 Radiant and All-Air Buildings. Building and Environment 126: 431–41. https://doi.org/10.1016/j.buildenv.2017.10.024.

Kim, J., de Dear, R., 2012. Impact of different building ventilation modes on occupant expectations of the main IEQ factors. Building and Environment 57, 184–193. doi:10.1016/j.buildenv.2012.05.003

Langevin, J., Wen, J., Gurian, P.L., 2012. Relating occupant perceived control and thermal comfort: Statistical analysis on the ASHRAE RP-884 database. HVAC&R Research 18, 179–194. doi:10.1080/10789669.2011.607882

Leaman, A., Bordass, B., 2013. Are users more tolerant of "green" buildings? Building Research & Information 35, 662–673.

McCartney, K.J., Nicol, J.F., 2002. Developing an adaptive control algorithm for Europe. Energy and Buildings 34, 623–635. doi:10.1016/S0378-7788(02)00013-0

Paciuk, M., 1990. The role of personal control of the environment in thermal comfort and satisfaction at the workplace. Environmental Design Research Association 21, 303–312.

Rethinking user behaviour comfort patterns in the south of Spain - What users do

Samuel Domínguez Amarillo[1], Jesica Fernández-Agüera[2] and Juan José Sendra[1]

[1] Institute of Architecture and Construction Sciences, School of Architecture, University of Seville, Spain. sdomin@us.es
[2] Eduardo Torroja Institute of Construction Sciences, Higher Council of Scientific Research, Madrid, Spain. jfernandezaguera@us.es

Abstract: Any investment made in refurbishing buildings in order to limit their energy demand can generally be classified as being of strategic interest. However, we have found that, although the application of current energy analysis techniques can imply significant potential energy savings when retrofitting housing stock, it is often the case that significant deviations from the envisaged energy performance can come about, in particular in southern Europe. A monitoring process has been carried out in occupied dwellings over a long, continuous period of time, in order to obtain values of over one year of duration of multiple environmental variables, most notably the indoor air temperature readings, relative humidity and HVAC operation. This monitoring has been completed with a series of surveys on the behavioural habits of tenants, in order to obtain correlations between energy consumption and their behaviour comfort patterns. This work has demonstrated that there is generally no direct relation between official and real user comfort patterns in social housing in southern Spain. Indeed, energy consumption tends to be lower than expected, due mainly to the fact that inhabitants spend long periods in unsuitable living and health conditions. This information has been used to generate a real comfort behaviour pattern.

Keywords: thermal comfort, climate-control system use patterns, monitoring of environmental variables, user behaviour comfort patterns.

1. Introduction

Given that the first mandatory measures to limit overall energy demand in buildings did not come into effect until the Basic Building Standard on Thermal Conditions in Buildings, NBE CT-79 (Spanish Government RD 2429/79), was promulgated, and, furthermore, that building policies based on expansion rather than speculation have focused more on new builds than on refurbishments, there is a high percentage of residential buildings constructed without effective thermal insulation measures and with significant deficiencies in terms of current energy standards, in addition to insufficient conditions of well-being and hygiene, i.e. with clear signs of obsolescence.

We must be aware of the role of social housing stock in today's cities, and of the importance of dwellings built in the period between 1939-79. In the case of Seville, more than 48% of residential blocks were built between 1939 and 1979 (Spanish Statistics National Institute, 2011). If we add those built at the beginning of the 20th century, the figure exceeds 51% of the current housing stock. More than half of the city's dwellings therefore have a certain degree of obsolescence, which varies from case to case. Of this percentage, the dwellings classified as "social" exceed 60% of the total. We can define this group of social housing as the group with the highest risk, since it accounts for more than 30% of all current housing in the city of Seville.

In general, the building envelopes of a large part of the current housing stock will, to a significant degree, be responsible for the environmental performance of these dwellings being far from what we today understand as desirable, and will also determine users' expectations. These aspects are particularly important in order to meet the requirements set out in European energy saving directives (European Commission, 2012) and the Horizon 2020 targets , along with national regulations that establish minimum environmental and energy requirements for residential buildings (Spanish Government RD 233/2013). Many of these regulatory requirements often refer to the construction of new buildings, establishing patterns of energy use and consumption which are far removed from the actual operation of the buildings. Recent studies (Branco, Lachal, Gallinelli and Webwe, 2004; Majcen, Itard and Visscher, 2013; Sunikka-Blank and Galvin, 2012), show that a large number of these buildings have significantly lower energy demands than estimated in the national energy assessment procedures derived from Directive 2002/91/EEC, in Spain (Spanish Government RD 235/2013). Current residential buildings generally have limited capability in terms of thermal control of the envelope and a general lack of thermal conditioning systems, resulting in an inability to control the indoor environment. This issue greatly affects less-wealthy population groups, who have limited resources to invest in artificial indoor control.

There is an almost complete absence of built-in technical climate-control systems (boilers or heat pumps) in social housing stock from the mid-20th century to the present. Inhabitants often solve part of the problem by using portable devices or room-size systems (i.e. split units), and can therefore only control some rooms in the best-case situation.

This behaviour may be explained by energy poverty situations (Sendra, Domínguez-Amarillo, Bustamante and León, 2013), users' social and cultural indoor-environment control traditions, similar to those in Europe's entire southern flank (Santamouris et al, 2014), and a geographical adaptation to less-demanding environmental comfort ranges, thus developing higher thermal-comfort tolerances.

A process of reflection is therefore required in order to improve the habitability and energy use conditions of existing dwellings, if these targets are to be achieved throughout the country.

The main aim of this research is to relate the information gathered on alternative energy use patterns to normal indoor conditions in social housing in this part of southern Europe, with a view to optimising the assessment of potential improvements in both.

2. Methodology

2.1. Monitoring

This methodology analyses the environmental conditions of social housing. In situ data collection of environmental variables is essential for evaluation of the environmental patterns of the case studies. For this reason, this research has monitored air temperature, relative humidity and CO_2 levels inside the dwellings. Two WOHLER CDL 210 indoor data-loggers were placed in each dwelling (one in the living room and the other in the main bedroom) to measure the variables every 30 min for a full year. The accurancy of the instruments are +-0.5 °C in temperature, +-3 % in relative humidity and +-50 ppm in CO_2 levels.Monitoring is carried out while the housing is occupied, allowing us to consider the influence of inhabitants' patterns on variations in energy consumption, in order to obtain user patterns.

The environmental variable characterisation data for the dwellings in this study come from two groups:

- 16 buildings included in the EFFICACIA project, which are representative of social housing in accordance with the NBE CT-79 regulation.

- 8 buildings included in the REFAVIV Project, which are representative of period 1939-1979 in accordance with none regulation.

The behaviour of each group of dwellings is characterised by applying statistical analysis techniques, identifying their different evolutions and the existence of patterns, in order to obtain temperature distribution probabilistic models for the different kinds of dwellings. Different probabilistic models of temperature distribution are generated:

- In the reference group (EFFICACIA project), winter and summer models, dividing the latter into cooled, non-cooled and periods in free evolution.
- In the contrast group (REFAVIV project), winter and summer models, in which the latter are exclusively of free evolution, since none of the dwellings of the group have cooling systems.

This monitoring has been completed with a series of surveys on the behavioural habits of tenants, in order to obtain correlations between energy consumption, air temperature and their patterns of behaviour and to avoid the usual divergence between real and estimated patterns of consumption (Prebound effect).

2.2. Location and climate

All case studies are located in Seville, which has a Mediterranean climate with mild winters and summers with very high temperatures. Table 1 summarises the main climate characteristics of this location.

Table 1: Seville climatic data. Average temperature (T), maximum temperature (TM) minimum temperature (Tm), relative humidity (H), solar radiation hours (I).

Month	T (ºC)	TM (ºC)	Tm (ºC)	H (%)	I (hours)
January	10.9	16.0	5.7	71	183
February	12.5	18.1	7.0	67	189
March	15.6	21.9	9.2	59	220
April	17.3	23.4	11.1	57	238
May	20.7	27.2	14.2	53	293
June	25.1	32.2	18.0	48	317
July	28.2	36.0	20.3	44	354
August	27.9	35.5	20.4	48	328
September	25.0	31.7	18.2	54	244
October	20.2	26.0	14.4	62	216
November	15.1	20.2	10.0	70	181
December	11.9	16.6	7.3	74	154

2.3. Description of case studies

The case studies are two groups of social houses in multi-family buildings:

- In the reference group (Sendra et al, 2011; Domínguez-Amarillo, Leó,Sendra, Esquivias 2012), dwellings built between 1990 and 2000 with different orientations and a mean floorspace of 65m^2. They all have thermal insulation in their envelope (façades and roof). There are two groups: a first group of dwellings with a reversible local heat pump in one or two bedrooms, and a second group with no thermal conditioning systems.
- In the contrast group (Domínguez-Amarillo, Sendra, Fernández-Agüera, Escandón, 2017; Domínguez-Amarillo, Sendra, Oteiza 2016), dwellings built between 1960 and 1979 with different orientations and a mean floorspace of 58m^2 (reference). As usual in social housing in southern Spain, most cases have no thermal conditioning systems, only portable electric air heaters.

3. Results

3.1. Reference group temperature

Figure 1 shows the temperature likelihood distribution for the entire winter season for the different dwellings in the sample. This analysis focuses on ascertaining how much this broad range of dwellings can be grouped together, as well as the dispersion of their tail areas. We can see how there is a marked difference in the temperature profile between the dwellings according to their orientation and whether they are under the roof. In general, it can be seen that there is a likelihood of over 80% (range 100-60%) of presenting temperatures below 20°C, while 19°C has a likelihood of occurrence of more than 60% (range 35-90%), which is particularly significant compared to usual standards of comfort. The basic procedure control base temperature is not reached for the rooms overall in more than 40% of the hours of the period.

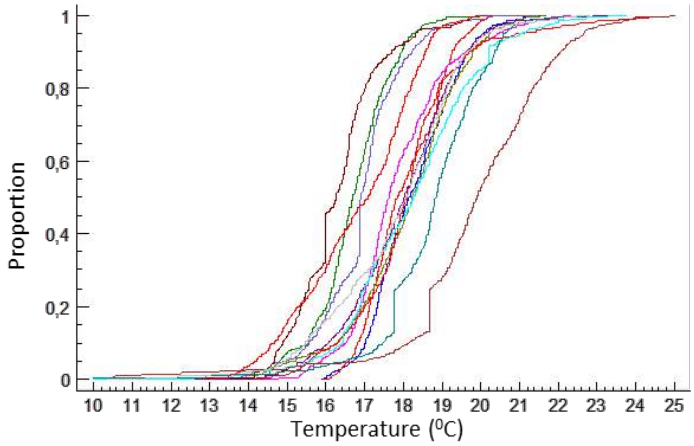


Figure 1: Graph of temperature (˚C) likelihood distribution quantiles, as measured in the dwellings during winter.

The evolution of daytime temperatures during winter for the control housing group has been represented in Figure 2, taking as a reference the setpoint temperatures (night and day) established to assess demand and the basic procedure for energy rating. Daytime variability is shown, as well as the difference in performance between dwellings. It is necessary to stress the important presence of low temperatures, along with the high temperatures which come about on warm days in winter.

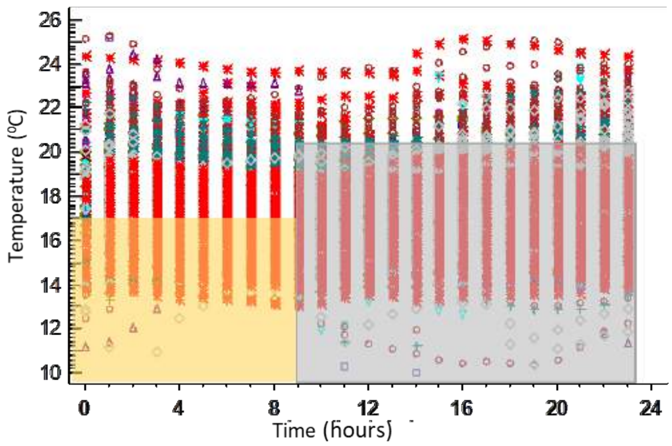


Figure 2: Distribution of daytime temperatures (°C) in the winter months in the group of dwellings compared to Heating setpoint temperatures, in accordance with the Energy Rating procedure and characterisation of CTE-HE demand. Night temperature setpoint (yellow) and day temperature setpoint (grey).

For analysis of the summer months, the sample has been divided into monitored dwellings with and without cooling systems, in order to compare users' behaviour.

Figure 3a shows the likelihood distribution for summer temperatures of the dwellings fitted with cooling systems; here we can see how, even though the dwellings have cooling systems in at least one of the rooms, the temperatures are generally high, with a significant presence of temperatures above 30°C in all of them (generally with more than 50% likelihood of this occurring), which indicates a very low intensity of use. It is also necessary to point out that the evening control temperature (25°C) is exceeded in practically the entire period; indeed, in only a few dwellings is this likelihood around 5%, allowing us to affirm that it is not representative of the setpoints used by the inhabitants of the dwelling.

The likelihood distribution for dwellings without cooling systems is shown in Figure 3b. In this case we can see that the temperatures are also high in general, with a smaller difference between the different distributions (greater grouping than in the case of dwellings fitted with climate-control equipment). 50% likelihood is around 30°C, and it is very rare for these dwellings to be below 26°C (distribution curve inflexion). Exceeding 31.5˚C is generally infrequent for most rooms (90% of time below).

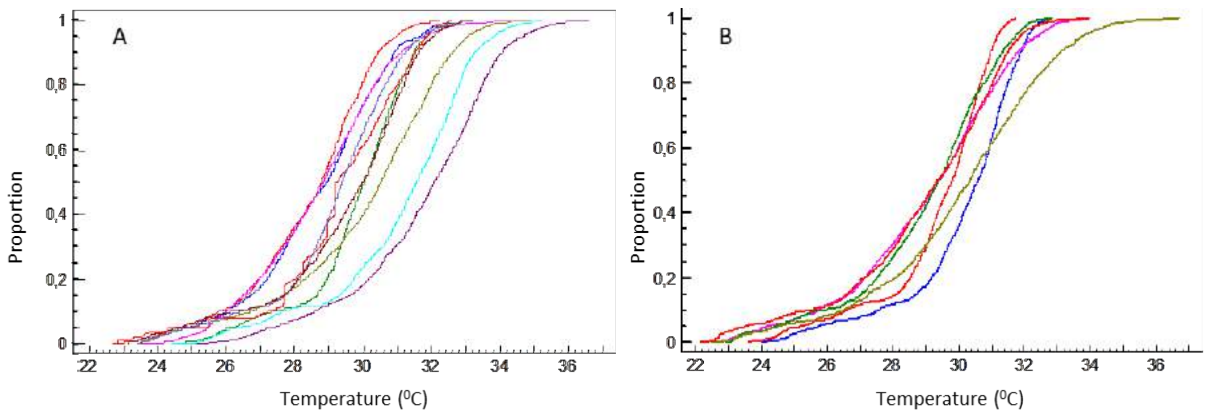


Figure 3: Graph of temperature (˚C) likelihood distribution quantiles, as measured in the dwellings with cooling equipment (a) and without cooling equipment (b) during the summer.

We can assume that the data for both daytime and night-time do not come from a normal distribution of each group of dwellings (with and without cooling). This means we can state, with a confidence of 95%, that 99.94% of the temperature values of the dwellings are within the range between the lower limit of 22.64°C and an upper limit of 35.3°C for the night-time period and 36.6°C for daytime (Figure 4). In the daytime period (Figure 4a), the median of the sample without cooling is 30.37°C, while in the sample with cooling it is 29.53°C, a difference of just 0.84°C. In the night-time period (Figure 4b), the median of the sample without cooling is 29.83°C, while in the sample with cooling it is 29.25°C, a difference of just 0.42°C. These figures indicate that the use of cooling has little effect on overall temperature, which shows little variation.

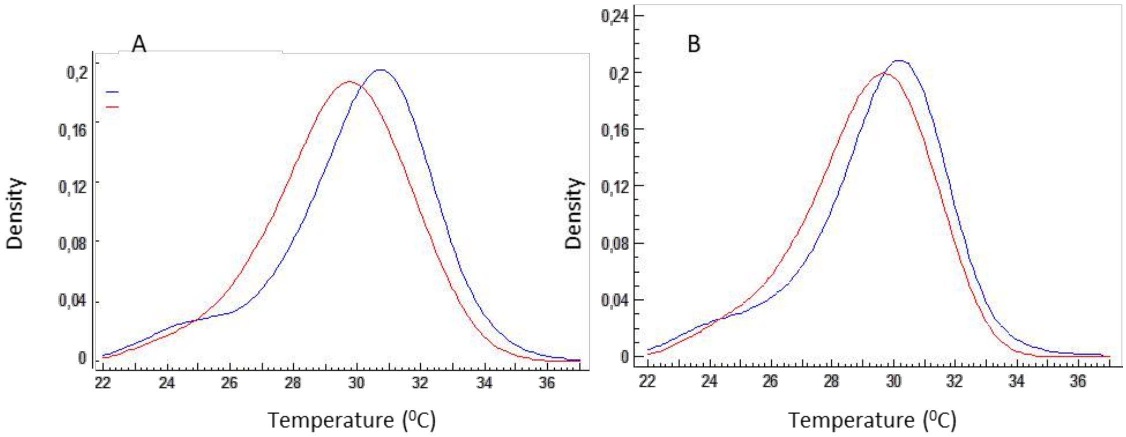


Figure 4: Comparison of density traces of summer temperature distributions (°C) for dwellings without cooling systems (blue line) compared to dwellings with cooling equipment (red line) during the day from 8 a.m. to 11 p.m. (a) and at night from 11 p.m. to 8 a.m. (b).

In this case the CTE-HE basic procedure determines three periods: the main period for climate control is the evening period, which lasts from 4 p.m. to 11 p.m., in which there is stricter control of the dwelling thanks to the operation of the cooling systems, with a high setpoint temperature of 25°C. This is followed by the night-time period, from 11 p.m. to 8 a.m. the following day, during which control is less intense, and ventilation of the dwelling is largely entrusted to its conditioning, although with a secondary control programme which determines the use of cooling when the temperature exceeds 27°C (meaning this temperature should not be exceeded in any case). The operating pattern defined by the basic procedure (unlike the winter period, when the dwelling is permanently under climate control) establishes a central band in the day with the dwelling in free evolution, without any temperature control. This period lasts from 8:00 a.m. to 4:00 p.m., when the dwelling changes to artificial thermal control.

Figure 5 shows that the minimum temperatures in the dwelling are reached early in the morning, shortly before 8:00 a.m., with a value of 28.8 °C (SD= +-1,6 °C) ; the temperature then rises until maximum temperature is reached at the end of the day (29.55ºC after about 10 p.m.) and begins to drop again. A turning point in the model can be appreciated around 4 p.m., when the temperature increase trend changes; this can be associated with the operation of the cooling systems, which modulate temperature increases despite the arrival of the external thermal wave.

This profile does not indicate constant use of thermal control (cooling) systems, since the variations are slight between periods theoretically in free evolution and the possible use of the systems. Moreover, temperatures are very far from those in regulatory standards. In consequence, the temperature measurement indicates that cooling systems are not used continuously, but rather sporadically as a way of resolving specific moments of excess temperature.

It can be seen (Figure 5) how the heat accumulated during the day is dissipated during the night (fundamentally by means of nocturnal ventilation processes, without any sudden reductions being appreciated) through to the start of the day, at which point the dwelling accumulates energy again, therefore raising its temperature. As in winter, it can be seen how the temperature descent slope (discharge) during the night is more pronounced than the temperature ascent period (load), which is much more spread out over time. In this case the action of the occupants is not appreciable in any significant manner.

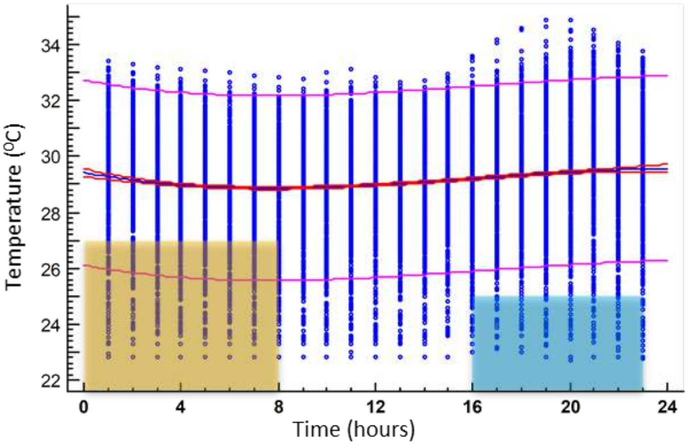


Figure 5: Distribution of daytime temperatures (°C) in the summer months in the group of dwellings compared to Cooling setpoint temperatures, in accordance with to the Energy Rating procedure and characterisation of CTE-HE demand. Night temperature setpoint (ochre) and afternoon temperature setpoint (blue).

3.2. Comparison between contrast and reference group temperature

In general, it can be seen how the dwellings in the reference group could be classified as warmer than those of the contrast group prior to year 1979. The mean temperature values in the latter are always lower, and, in general, tend to present a more stable performance with temperatures grouped around the central values, which shows the lowest standard deviation of values in the daily period (Table 2).

Table 2: Mean temperatures

Dwellings	Season	Period	Mean	SD
Constract group	Winter	Day	15,35	1,12
		Night	15,38	1,16
	Summer	Day	27,30	0,85
		Night	26,90	0,87
Reference group	Winter	Day	17,97	1,69
		Night	17,82	1,61
	Summer	Day	29,97	2,35
		Night	29,70	2,15

It is significant that the values of the dwellings in the contrast group (the oldest) stabilise far from comfort values in winter, and, despite the local action of portable heaters and similar equipment, their mean and habitual values show a very high differential relative to desirable comfort conditions (this limit can be established for values above 20 ºC); on the other hand, the reference dwellings, which have thermal insulation, are similarly incapable of providing a general comfortable environment, and also count on discontinuous and local heating equipment, although the difference is practically half compared to the other group.

The variability of temperatures during the winter can be seen in the higher variation ratios in the reference group, and, associated to this, the temperatures of the exterior quartiles are more extreme than in the reference group, in other words they heat more and cool more.

In the group of dwellings without cooling systems, there is a daily wave with high amplitude, resulting in high daily temperatures which even surpass 30˚C. This situation is mitigated, albeit only slightly, by the intermittent action of cooling equipment, limiting daily oscillation to half that of dwellings without such equipment, and preventing the model temperature from exceeding 30˚C. In both cases, nocturnal dissipation capability is reduced, failing to reduce the temperature of the central values below 29˚C. However, the dwellings in the contrast group, despite not having cooling systems, show more stable performance with values typical of cooled spaces, generally within values which are suitable for adaptive or passive comfort, and daily amplitude is similar to that for the reference values with equipment (Figure 6).

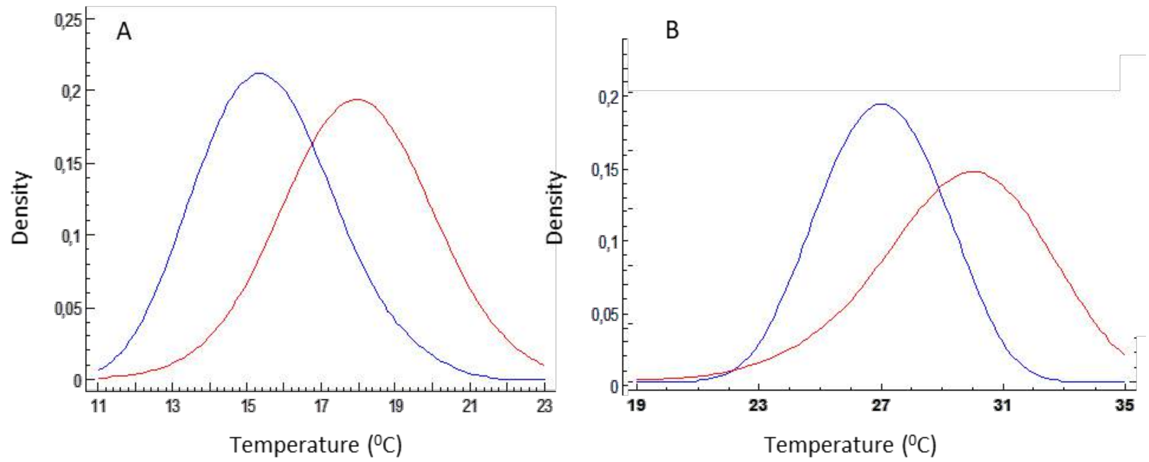


Figure 6: Comparison of adjusted temperature distributions (°C) of the group of dwellings without thermal insulation (blue) compared to the group of dwellings with thermal insulation (red) for the daytime period in winter (a) and summer (b).

3.3. CO_2 concentration

In winter season, bedrooms have CO_2 concentrations above 900 ppm for longer than living rooms. However, in the intervening season these percentages are reversed. In summer, the concentration of CO_2 in bedrooms is diluted due to night-time ventilation, while it is also high in living rooms throughout the day when they are occupied (Table 2).

Table 2: Number of hours and percentage of total hours in which dwellings have a CO_2 concentration above 900 ppm.

Month	Bedroom (hours)	Living-room (hours)
January	484 (65%)	320 (43%)
February	361(53%)	191 (28%)
March	285 (38%)	172 (23%)
April	0	106 (15%)
May	239 (32%)	320 (43%)
June	290 (40%)	320 (44%)
July	222 (30%)	0
August	Holidays	Holidays
September	236 (33%)	24 (3%)
October	290 (39%)	32 (4%)
November	321 (44%)	230 (32%)
December	413 (55%)	321 (43%)

3.4. Surveys on patterns of use of thermal systems and ventilation

All of the users surveyed recognise that they implement passive control measures before starting up the climate-control system. In winter, the most popular options were: firstly, closing all doors and windows; secondly, wearing warm clothing; thirdly, turning on an auxiliary heater; and finally, turning on the main heating (only 35% of those surveyed). In winter the most popular options were to wear light clothing and, depending on the outside temperature, open doors and windows or turn on an auxiliary fan before starting up the cooling system.

Figure 7a shows the existence of active cooling systems in the dwellings surveyed: 16% do not have any system in the dwelling (C0), 21% use fans (C1), 53% local split systems (C2), and 10% a centralised cooling system (HVAC) (C3).

Figure 7b shows the existence of heating systems in the surveyed dwellings: 5% have no system in the dwelling (H0), 11% water radiators (H1), 5% butane or propane heaters (H2), 63% electrical appliances such as radiators or heaters (H3), and 16% air conditioning with heat pump for heating (H4).

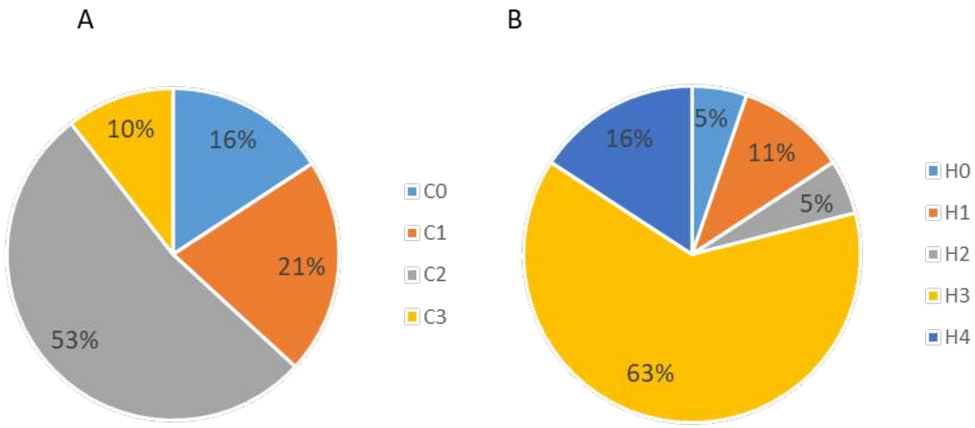


Figure 7: Availability of cooling (a) and heating (b) equipment in the surveyed dwellings.

Figure 8a shows the answer to the question of how many weeks a year the heating and cooling systems are used, where it can be seen that the heating system is used for longer than the cooling system. Surveyed users acknowledge that 5% of them do not use any type of heating system, compared to 26% who do not use the cooling system on any day of the year. 48% of respondents use the heating system for more than 13 weeks a year, compared to 16% for cooling.

Figure 8b shows the answer to the question of use of climate-control systems at night during periods of extreme temperatures in winter or summer. 58% of respondents said they did not use night-time heating and 48% did not use the cooling system. 26% of respondents said that they turned the heating system on at night every day of the week at the coldest times of year, while in summer only 5% use it every day, although 21% answered almost every day.

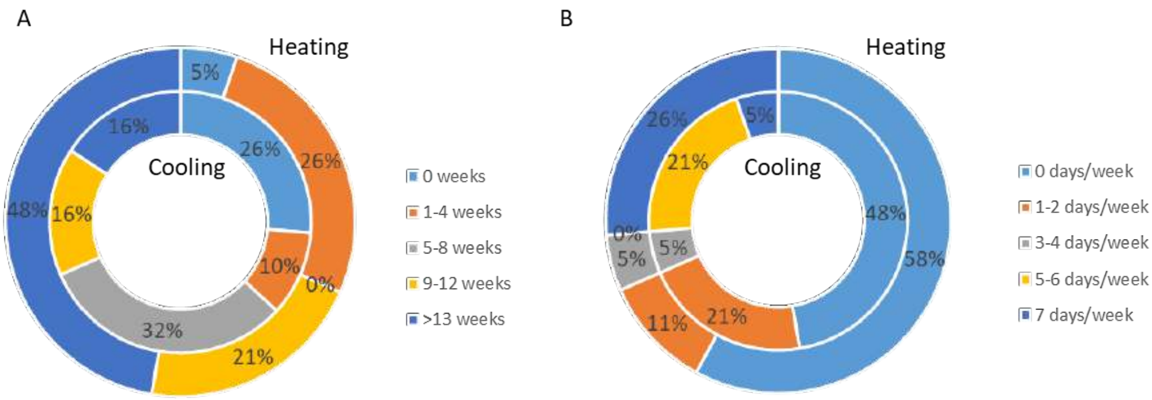


Figure 8: Weeks of use of climate-control systems (a) and night-time use of climate-control systems (b).

Figure 9 represents variability in the ventilation habits of users of the dwellings during the summer and winter seasons. In winter, only 5% of respondents answered that they do not ventilate their home, with the most frequent response (58%) being that they ventilate their home once a day, followed by twice a day (21%) and four times a day (16%); however, ventilation generally takes place in very short periods, with 67% of respondents stating that they ventilate for less than 30 minutes overall (Figure 9b), generally between 8 and 10 a.m. In summer, the most frequent response is that they ventilate the dwelling twice a day (53%), although the daytime ventilation period is much longer than in winter (Figure 9c), with figures showing 57% more than one hour and 26% more than 5 hours. The times for ventilation are early in the morning and at dusk, with night-time ventilation removing the need to use cooling systems.

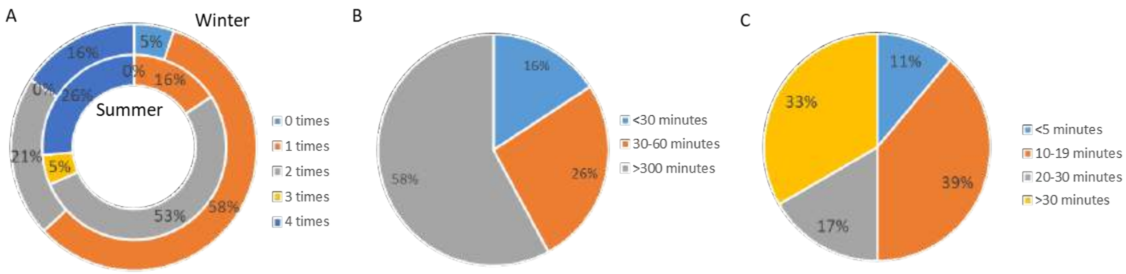


Figure 9: Number of times the dwellings are ventilated according to season (a) and daytime ventilation time in winter (b) and summer (c).

3.5. Alternative scenario proposal

An alternative scenario to that established in Spanish legislation is proposed as part of the discussion of the results and as a response to the monitoring of variables and the analysis of user surveys. This scenario is introduced for a realistic assessment of use of energy in the dwelling (especially for social housing), the occupancy profile, and the use of thermal conditioning systems (by modifying the control setpoints). Values derived from observing the actual performance of dwellings are adopted, which have been discussed in previous sections and are shown in Table 3. This makes it possible to obtain results that are more in line with the actual performance of the social dwelling, as well as a more reliable assessment of potential savings potential.

Table 3: Setpoint temperature programme for the alternative scenario (B)

Setpoint temperature (°C)	1-7 h	8 h	9-15 h	16-23 h	24 h
January to May (lower)	15	19	19	19	15
June to September (higher)	*l.evo*	*l.evo*	*l.evo*	27	*l.evo*
October to December (lower)	15	19	19	19	15

There is an adjustment of the heating operation temperatures during the winter, even though the timetable is the same. During the daytime period the temperature is set to a lower value (understood as the mean temperature of the dwelling, since there may be rooms with a locally higher temperature, and vice versa, depending on the use of the heating equipment). Use of heating is not envisaged at night, which is understood as a period of free evolution. An exception has been introduced to the effect that users operate a heating system in the event of extraordinary periods during which the temperature may fall below 15°C.

There is a similar situation for the summer period, i.e. it has been observed that there is no significant use of cooling in the mornings (given the low occupancy profile of the dwelling in this period). Cooling is only used in the evening period, with an adjustment of the operating temperature in accordance with the observed values of the highest thermal tolerances. The use of active cooling systems has not been considered for the night-time period since cooling is provided through the use of natural ventilation, with the dwelling passing to free evolution.

4. Conclusions

4.1. On assessment of the habitability of the housing stock

The dwellings in the contrast group –social dwellings dating from before the incorporation of general insulation requirements– are far from the conditions habitually defined as being comfortable for mechanically conditioned spaces, and, furthermore, are often outside of the ranges defined even for adaptive comfort strategies for buildings without mechanical systems (fundamentally focused on passive mitigation of thermal excess, but little suited to heating situations). It can therefore be established that occupants are exposed to unsuitable habitability conditions for prolonged periods of time.

There is a low ventilation level of the dwelling during the cold season, both voluntary and natural. This situation, which is critical to ensure indoor health conditions, is associated with the following factors: reluctance to make openings in walls for ventilation, due to inability to treat the associated thermal load; absence of mechanical equipment which ensures air renewal; relatively high airtightness of the dwelling (when the window frames have been replaced); and low infiltration capacity to produce the renewal of the indoor atmosphere.

On the other hand, during the summer the dwellings are generally in conditions of over-ventilation (as a passive thermal control measure), which devalues the capability of the envelope to act as an energy moderator, while the absence of general cooling systems means an increase of the mean temperatures above comfort values (the application of adaptive comfort strategies is possible during some periods of time outside of the most extreme conditions). This situation mainly affects indoor comfort conditions, although the existence of repercussions on health cannot be discarded. In summer, the reference group is two degrees worse than the contrast group.

4.2. On thermal conditions systems

In view of the analyses completed, it could be expected that the installation of thermal conditioning systems in the social housing of the study period would be fundamentally of local type, i.e. heating units which treat a single room or which can be moved about, in many cases including capability to treat several rooms in the dwelling. Such heating units use electricity, almost exclusively, as the power source for thermal treatment of the dwelling. Coexisting alongside this prototypical facility there are dwellings with no form of heating (or in which it is so insignificant that it is not declared) or with a single unit for the entire dwelling, generally a split heat pump system.

Based on this initial situation, any subsequent installation is conditioned by different aspects which have resulted in the current distribution: the physical limitations of the dwellings, since the layout and available space make it difficult to retrofit, and, above all, the cost of investment, which is generally high and is a fundamental factor in dissuading people.

Moreover, their introduction in collective thermal systems, which lack communal spaces for the storage of fuel, boiler room and pipe layout, is equally problematic. Their high initial cost, plus the absence of any tradition of collective systems in the city, means there is no record of any subsequent process of incorporation of such facilities.

The common solution would be the gradual acquisition of portable heating units (heaters, fires, etc), since these are inexpensive to purchase and have low maintenance costs, which would subsequently be supplemented with portable heat pump equipment (local), normally in a split configuration. The latter solution is preferred to larger facilities covering the whole dwelling, as such an implementation is much more expensive and requires significant building work, most notably the installation of ducts. Moreover, there must be enough space to install the indoor unit (usually in a bathroom or kitchen), which is often infeasible in these dwellings, since the free height available is generally very limited (in many cases 2.4 to 2.5 m). The absence of false ceilings in these dwellings, in particular the older ones, also makes the installation of ducts impractical and expensive.

It is important to stress that, given the current structure of the thermal systems and capabilities of the housing stock studied, these buildings make a marginal contribution to local contaminating emissions, unlike in other cities where local emissions associated with thermal conditioning (fundamentally heating) play an important role in the atmospheric quality of the city.

Notwithstanding, the impact on indirect emissions related to the use of conditioning systems in the housing stock must be considered. Since this sector is fundamentally dependent on electricity, its role in indirect emissions on overall CO_2 is higher than that associated with other energy sources.

5. References

Branco, G., Lachal, B., Gallinelli, P., Weber, W., 2004. Predicted versus observed heat consumption of a low energy multifamily complex in Switzerland based on long-term experimental data. Energy and Buildings, 36, pp 543–555.

Domínguez-Amarillo, S., Sendra, J.J., León, A.L., Esquivias, P., 2012. Towards energy demand reduction in social housing buildings: envelope system optimization strategies. Energies, 5, pp 2263–2287.

Domínguez-Amarillo, S., Sendra, J.J., Fernández-Agüera, J., Escandón, R., 2017. La construcción de la vivienda social en Sevilla y su catalogación 1939-1979. Sevilla. Editorial Universidad de Sevilla. ISBN 978-84-472-1829-5.

Domínguez-Amarillo, S., Sendra, J. J., Oteiza, I., 2016.La envolvente térmica de la vivienda social. El caso de Sevilla, 1939 a 1979. Editorial CSIC. ISBN 978-84-00-10124-4.

EFFICACIA Project. Reducción del consumo energético y del impacto ambiental en la construcción de viviendas protegidas en Andalucía. Corporación Tecnológica de Andalucía (ref. 07161D1A)

European Commission and Parliament Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency; Brussels, Belgium.

Majcen, D., Itard, L.C.M., Visscher, H., 2013. Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: discrepancies and policy implications. Energy Policy, 54, pp 125–136.

REFAVIV Project. Rehabilitación energética de las fachadas de viviendas sociales deterioradas aplicando productos innovadores nacionales (DIT) y europeos (DITE). Ministerio de Economía y Competitividad, Gobierno de España, Plan Nacional I+D+i (ref. BIA2012-39020-C02-01)

Santamouris, M., Alevizos, S.M., Aslanoglou, L., Mantzios, D., Milonas, P., Sarelli, I., Karatasou, S., Cartalis, K., Paravantis, J.A., 2014. Freezing the poor—indoor environmental quality in low and very low income households during the winter period in Athens. Energy and Buildings, 70, pp 61–70.

Sendra, J. J., Domínguez-Amarillo, S., León Rodríguez, A. L., Navarro, J., Muñoz, M. S., 2011. Proyecto EFFICACIA Project. Optimización energética en la vivienda colectiva. Secretariado de Publicaciones de la Universidad de Sevilla. ISBN 978-84-472-1376-4.

Sendra, J.J., Domínguez-Amarillo, S., Bustamante, P., León, A.L., 2013. Energy intervention in the residential sector in the south of Spain: current challenges. Informes de la Construcción, 65(532), pp 457–464.

Spanish government, Royal Decree RD 233/2013 of 5 April 2013; Madrid, Spain.

Spanish Statistics National Institute (2011). Censos de Población y Viviendas2011. Available at: http://www.ine.es/censos2011/tablas/Inicio.do. (Accessed 1 January 2018).

Spanish government, Royal Decree RD 2429/79 of 6 July 1979 , por el que se aprueba la normativa básica dela edificación NBE-CT-79, sobre condiciones térmicas en los edificios. Madrid, Spain, 1979.

Spanish government, Royal Decree RD 235/2013 of 5 April 2013; Madrid, Spain, 2013.

Sunikka-Blank, M. Galvin, R. 2012. Introducing the prebound effect: the gap between performance and actual energy consumption. Building Research and Information, 40, pp 260–273.

Acknowledgement

This study was funded by the Spanish Ministry of Economy and Competitiveness under project BIA2012-39020-C02-01 and BES-2013-063097 support.

What do households do to keep cool?

Gary Raw

UCL Energy Institute and GR People Solutions, rawgj@hotmail.com

Abstract: With climate change in mind, we need effective strategies to avoid overheating in homes – strategies built on an understanding of what households currently do to keep cool and why they do it. This paper reports findings from a survey of 2,313 households, supported by literature review and qualitative research. Only 9% of respondents say that it would not get too warm on a typical summer day. The actions taken to avoid overheating are often successful but there remain 27% who do not always keep cool enough on a typical summer day. Even in winter, a majority need to avoid overheating, and households that report always feeling warm enough in winter are more likely to overheat in winter. This suggests potential both to improve comfort and to reduce energy use. Households avoid overheating partly by controlling room temperature but a majority also use methods targeted at themselves: reducing clothing/bedding, cooling the body, or changing location. Behaviour varies with characteristics of both the dwelling and the household, and reflects needs beyond thermal comfort. A majority of households do open windows but also report barriers to doing this (e.g. security or noise). Reducing barriers should facilitate cooling without air conditioning.

Keywords: Overheating, Cooling, Household behaviour, Comfort, Energy

1. Introduction

Along with having the means to keep warm, it is important that homes should not overheat. This study explored how households currently try to avoid getting too warm, in both summer and winter, and whether they succeed. This understanding is important in developing effective means to keep cool that avoid unnecessary use of expensive or energy-consuming solutions.

2. Method

The study comprised a quantitative social survey of a representative sample of 2,313 British households. The method is described in detail elsewhere (Raw *et al* 2017) and briefly summarised here. The survey was developed from extensive literature review and qualitative research into heat energy needs and behaviours (National Centre for Social Research 2014, Raw & Littleford 2014). Respondents completed a face-to-face interview in their homes. The interview covered behaviour, motives and systems related to cooling, plus household and dwelling characteristics. Individual questions are detailed below, together with the related findings.

Unless stated otherwise, the percentages reported are based on 2,287 respondents who answered sufficient questions on cooling. Because the survey was conducted in winter, some respondents had not experienced a summer in their current home, which reduced the base for the relevant questions to 2,106.

3. Findings

3.1. Overheating in summer

3.1.1. What households do to keep cool in summer

Respondents were asked "Please say which of these things, if any, you or your household sometimes do to avoid getting too warm on a typical summer day (not when there is a heatwave)?" Respondents could either say that it would not get too warm in summer or select as many other options as they wished. Households' strategies for keeping cool can be described at a range of levels (Table 1). Only 9% of respondents said it would not get too warm on a typical summer day and, on average, respondents selected 5.6 options.

Table 1 Strategies to avoid getting too warm in summer

Level 1	*Level 2*	*Level 3*	*Level 4*	*Level 5*	*%*
Would not get too warm					9
Do something to avoid getting too warm	Environment-focused	Control heat gain	Turn heating down or off		60
			Shading	Internal	25
				External	4
		Remove heat	Natural ventilation	Windows (day)	79
				Windows (night)	53
				External doors	40
			Mechanical ventilation	Extract only	4
				Supply & extract	1
				Supply & extract + heat recovery	
			Air circulation within building	Internal doors	35
				Doors to shared parts	13
			Air conditioning	Hired	<1
				Present in the home	2
				Heat pump	<1
	Self-focused	Insulation	Clothing		53
			Bedding		48
		Cooling	Fan		29
			Drink		39
			Bath/shower		18
			Rest		8
		Change location	Indoors		6
			Outdoors		29
			Away from home		5

The most prevalent group of strategies is natural ventilation: 84% of households adopt at least one such measure (on its own in 55% of households and with other methods in 29%) – see Tables 2 and 3. In reality, probably additional households keep cool by opening windows but do not report this because they have windows open anyway, for other reasons.

The second most prevalent strategies (each reported by 60% of households) are changing clothing/bedding and reducing heat input (turning heating down/off) but only 2% reduce heat input and do nothing else. It is likely that others do not report reducing heat input because the heating is not used in summer. Fewer (26%) use shading, and only 4% use shading in the most effective location (on the outside of windows). Only 2% sometimes use mechanical cooling: heat pumps in 4 households, portable air conditioning vented to the outside in 19, portable air conditioning vented inside the home in 13, and fixed air conditioning in 14.

Table 2 Grouped strategies to keep cool in summer

Strategy (grouped)	*% of households*
Natural ventilation	84
Clothing/bedding	60
Reduce heat input	60
Cooling the body	55
Circulate air within building	36
Choice of location	33
Shading	26
Mechanical ventilation	4
Mechanical cooling	2

Table 3 Combined strategies to staying cool in summer

Combined strategies	*% of households*	
Reduce heat input only	2	2
Reduce heat input plus natural ventilation, with or without anything else	55	84
Do not reduce heat input; natural ventilation, with or without anything else	29	
Reduce heat input plus anything other than natural ventilation	3	5
Do not reduce heat input; anything other than natural ventilation	2	

3.1.2. Do households keep cool enough in summer?

All respondents (except those who indicated that it never gets too warm in summer) were asked "When you are doing this on a typical summer day, does this always keep you {and everyone in your household} cool enough?" The survey thus identified two groups who always keep cool: those who do not need to do anything specific and those who do something and it succeeds. These two groups, 9% and 64% respectively, together make up 73% of households. A further 25% sometimes keep cool enough and 2% rarely or never keep cool enough. Further analysis compared the 73% who always keep cool enough on a typical summer day with the 27% who do not (Table 4).

The oldest households (all over 60) are most likely, and those with preschool children are least likely, always to keep cool enough. Also, 10% of the oldest households state it would not get too warm in summer, compared to 5% of those with preschool children. Household size has a more complex effect. Single-person households and the largest (five or more) are most likely to state it would not get too warm in summer (10%). This pattern changes once the measures taken to keep cool accounted for: households of three or of five or more are the least likely always to keep cool enough. The percentage saying it would not get too warm in summer varies little with whether somebody is usually at home during the day.

Those in the lowest income quartile are twice as likely to say it would not get too warm in summer (12%) compared to other quartiles (all 6%) and hence less likely to engage in behaviours to stay cool. This effect disappears once the success of measures to keep cool is taken into account: higher earners are more likely to feel the need to do something but what they do is successful in keeping cool. Related to this, households renting from social landlords are more likely to say it would not get too warm in summer (12%) compared to those renting from private landlords or owning their home (both 8%). When the measures that households take are accounted for, owner-occupiers become the least likely to overheat.

Those in properties built before 1919 are most likely to say it would not get too warm (15% compared to 9% overall). Once the measures taken are accounted for, they are still less likely to overheat but differences are smaller and the newest homes (post-2001) are on a par with the oldest (both with 78% always being cool enough). Dwelling type does not affect the need to do something to keep cool. Once measures are taken, houses and bungalows are less likely to overheat than flats and maisonettes.

Table 4 Keeping cool enough by household composition, dwelling type, household size and tenure

Combination	*Yes, always (%)*	*Yes, sometimes (%)*	*No, rarely or never (%)*	*Base*
Total	73	25	2	2099
Household with children under school age	67	29	5	147
Household with children started or completed school	70	28	2	498
Households with no children and at least one adult under 60	69	29	2	649
Households with no children and all adults over 60	78	20	2	805
Flat/Maisonette	67	31	2	407
Bungalow	74	23	3	280
House	74	24	2	1402
Single-person household	76	23	2	577
2 Household members	74	23	2	729
3 Household members	65	33	2	319
4 Household members	73	25	2	296
5 or more Household members	68	29	3	177
Own	74	25	1	1411
Social landlord	71	26	3	410
Private landlord	68	29	4	244

3.1.3. Additional strategies to keep cool in summer

Respondents (again excluding those who had said it never gets too warm in summer) were asked "Are there any things on this list that you {and your household} do when your usual ways of keeping cool in summer are not enough (for example, on really hot days)?" While 7% of households would always be cool enough and another 35% report doing nothing extra, more than half of households use additional means when their usual strategies are not enough (Figure 1).

There is no overriding strategy; most options individually are undertaken by less than 20% of households with the most prevalent being to open windows during the day (21% of households). The effect of this is that, if it gets warm enough, almost all households open windows. Only 14 households (0.6%) hire air conditioning.

Older households (all over 60) are slightly more likely to do nothing extra: 38% compared to 35% overall. Owner occupiers and those who rent from a social landlord are more likely to do nothing extra (36%) than those who rent from a private landlord (29%). There is no clear overall trend and relatively little variation with dwelling type, age of dwelling or household income.

Respondents were then asked "In which of these circumstances, if any, do you do more to keep cool at home in summer?" Unsurprisingly, as shown in Figure 2, the weather being particularly hot is the main reason for doing more (71% of households). The next most frequent option (15% of households) is when someone at home is unwell. All other options were chosen by under 10%.

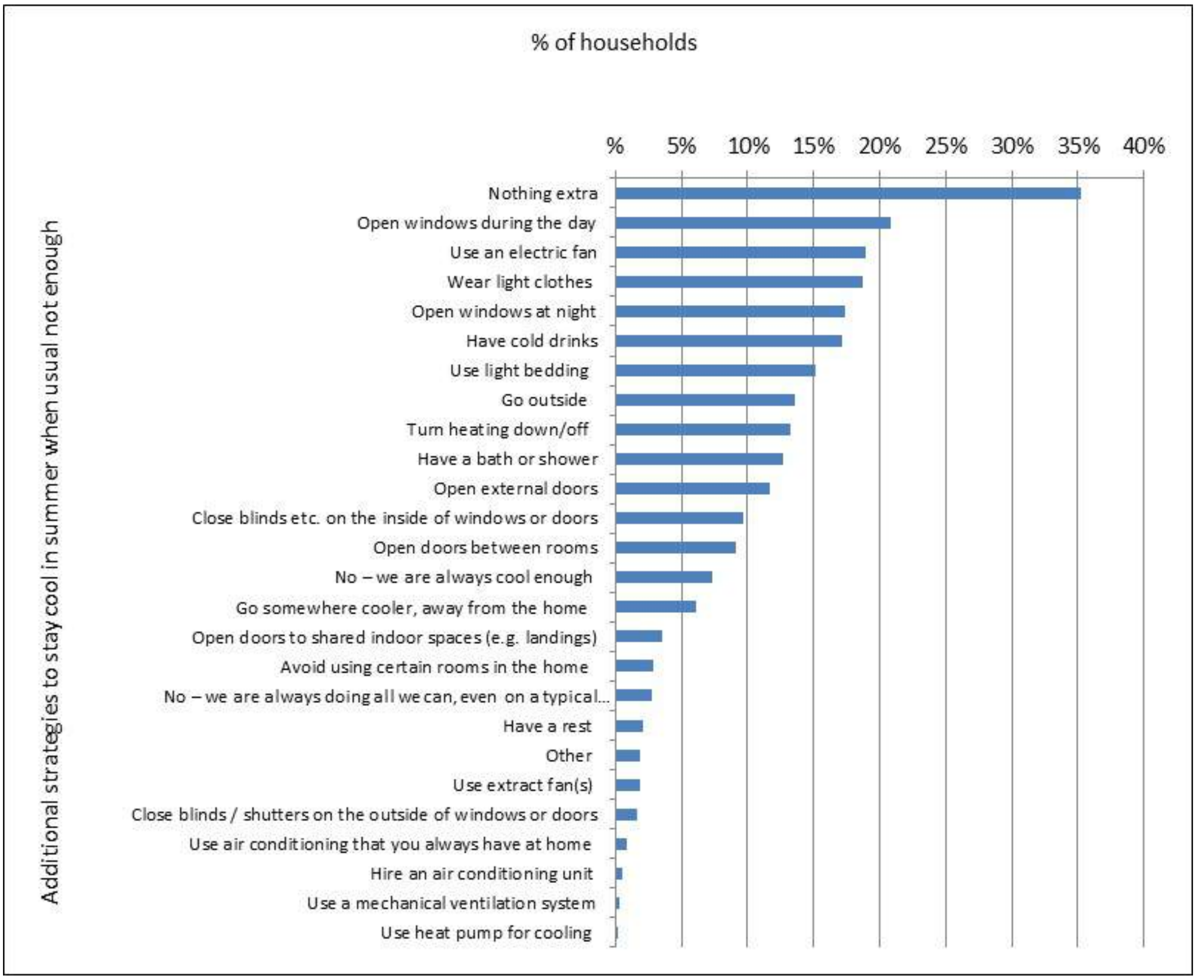


Figure 1 Additional strategies when usual ways to keep cool are not enough[1]

Overall, 23% change their behaviour in none of the listed circumstances. Older households (all members over 60) are least likely to change behaviour, 28% saying they would not change their behaviour in any of the listed circumstances. This is the case for only 16% of households with preschool children and 19% of those with older children. More specifically, households with children are more likely to do something extra when someone at home is unwell: 20% of those with children under school age and 21% of those with children started

[1] Base: all those that indicated that it can get too warm in the summer (1914).

or completed school, compared to 10% of the oldest households (all over 60) and 13% of other adult households. It is not necessarily the children who are unwell but it is a reasonable assumption that it sometimes is. Among households with children who had started or completed school, 22% do something different during school holidays.

There is no large variation by income except that those in highest quartile are more likely to change their behaviour when someone is working from home (18% compared to 6% in lowest quartile), which likely reflects the relative prevalence of working from home. There is no overall trend or large variation by dwelling type, age of dwelling or tenure.

3.2. Overheating in winter

3.2.1. What households do to avoid overheating in winter

Respondents were asked: "Please tell me which of these things, if any, you {or your household} sometimes do to avoid getting too warm in winter." Respondents could either say that it would not get too warm in winter or select as many other options as they wished. As in the summer, strategies can be described at a range of levels (Table 5). The overall pattern is similar to the summer (with lower percentages) except that more respondents say that it would not get too warm and reducing heat input is more prevalent.

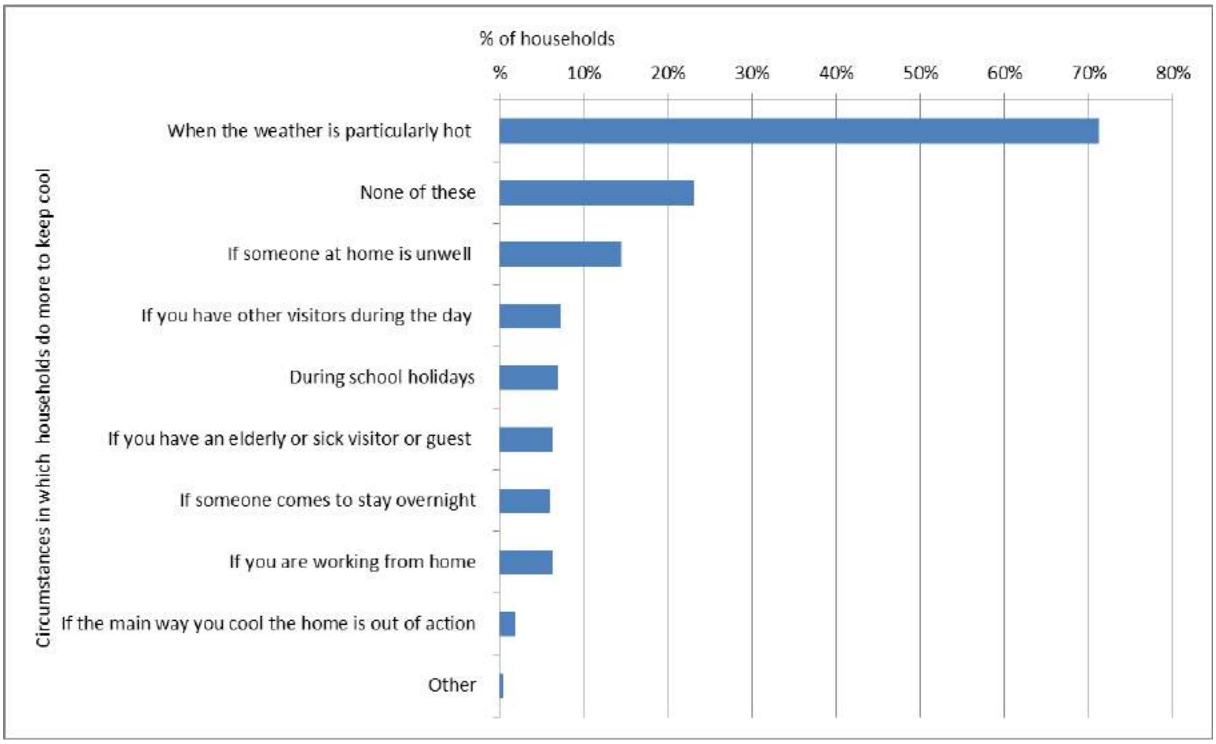


Figure 2 Circumstances in which households do more to keep cool

Table 5 Strategies to avoid getting too warm in winter

Level 1	*Level 2*	*Level 3*	*Level 4*	*Level 5*	*%*
Would not get too warm					37
Do something to avoid getting too warm	Environment-focused	Control heat gain	Turn heating down or off		50
			Shading	Internal	5
				External	1
		Remove heat	Natural ventilation	Windows (day)	28
				Windows (night)	14
				External doors	8
			Mechanical ventilation	Extract only	1
				Supply & extract	<1
				Supply & extract + heat recovery	<1
			Air circulation within building	Internal doors	14
				Doors to shared parts	5
			Air conditioning	Hired	<1
				Present in the home	<1
				Heat pump	<1
	Self-focused	Insulation	Clothing		18
			Bedding		12
		Cooling	Fan		6
			Drink		8
			Bath/shower		3
			Rest		2
		Change location	Indoors		1
			Outdoors		7
			Away from home		1

While 37% of households do not need to do anything specifically to avoid overheating, this does not mean that they are doing nothing: it is just that what they do normally is sufficient. The 63% that sometimes do something to avoid overheating do not necessarily all get too warm: they might avoid overheating through the actions they take. Nevertheless, the fact that so many need to do something to avoid overheating in winter indicates potential for improved control of heating both to improve comfort and to save energy.

Table 6 shows grouped strategies. The single most prevalent strategy (50% of households) is to reduce heat input. Some of those who do not report reducing heating might have their heating well controlled by a thermostat. Another 34% of households use natural ventilation. The third most prevalent group of strategies is to change clothing and/or bedding.

Table 7 shows the main combinations of methods that households use to avoid overheating in winter. In 50% of cases (80% of those who do something), the strategy involves reducing heat input, most often in a combination involving natural ventilation. This leaves 13% who do something else in preference to reducing heat input (again, most often in a combination involving natural ventilation). Only 19% rely solely on reducing heat input.

Table 6 Grouped strategies to avoid getting too warm in winter

Strategy (grouped)	*%*
Reduce heat input	50
Natural ventilation	34
Clothing/bedding	21
Circulate air within building	15
Cooling the body	13
Choice of location	8
Shading	5
Mechanical ventilation	1
Mechanical cooling	<1

Table 7 Combined strategies to avoid getting too warm in winter

Combined strategies	*Percentage*	
No specific action	37	
Reduce heat input only	19	50
Reduce heat input plus natural ventilation, with or without anything else	24	
Reduce heat input plus anything other than natural ventilation	8	
Do not reduce heat input; natural ventilation, with or without anything else	10	13
Do not reduce heat input; anything other than natural ventilation	3	

3.2.2. Who does what to avoid overheating in winter?

Respondents were asked what methods they usually use to keep warm and then asked "When you are doing that on a typical winter's day, does it always keep you {and your household} warm enough?" Only 72% stated that those typical actions 'always' keep them warm enough. Table 8 splits the sample into four groups, depending on whether, in winter, they sometimes overheat and whether they are always warm enough. Among those who always feel warm enough, a large majority sometimes overheat in winter. Among those who do not always feel warm enough, similar numbers do and do not sometimes overheat in winter. This suggests some conflict between ability to keep warm and ability to avoid overheating in winter. This is also seen in some of the following findings on the dwelling and household characteristics associated with overheating.

The percentage saying they would not get too warm increases with the age of the youngest household member (Table 9). The same trend can be seen for the percentage saying it is always warm enough, except for the higher percentage for households with preschool children. The effect of household size is similar to that seen in summer but will less variation.

Table 8 Percentage of respondents who are always warm enough vs sometimes overheating

	Always warm enough	*Not always warm enough*
Sometimes overheat in winter	49%	14%
Do not overheat in winter	23%	13%

Table 9 Respondents who are always warm enough and would not get too warm, by household type

Household type	*% in each household type*	
	Would not get too warm	*Always warm enough*
Children under school age	28	73
Children started/completed school	35	67
No children at least 1 adult under 60	37	68
No children all adults over 60	40	80
All households	37	72

Those in the lowest income quartile are most likely to say it would not get too warm in winter (41% compared to 34% in the middle quartiles and 26% in the highest quartile).[2] Consequently, those in the highest quartile are more likely to engage in cooling strategies such as reducing heat input (63%) or opening windows during the day (32%) or at night (21%). The findings for whether the household always feels warm enough show the inverse of these effects: while 79% of those in the highest income quartile report always feeling warm enough, this declines to 78%, 74% and 65% in the second, third and fourth quartiles respectively.

A similar pattern is seen in analysis by tenure. Those who rent are less likely to report overheating: 42% renting from a social landlord say it would not get too warm in winter and 41% renting from a private landlord, compared with only 34% of owner-occupiers. In contrast, while 78% of owner-occupiers report that they always feel warm enough, this is the case for only 63% of other households.

Households in pre-1919 properties are most likely to say it would not get too warm in winter (45%) and those in the newest properties (2002 or later) are least likely (26%). Consequently, households in the newest properties are most likely to take action, e.g. reducing heat input (61%) or opening windows during the day (40%). This might partly be because pre-1919 properties generally have the lowest level of insulation and greatest thermal mass. Respondents with single glazing are more likely to say it would not get too warm in winter, compared to those with multiple glazing (43% and 36% respectively). In contrast, only 69% of people living in older properties (pre-1964) report always feeling warm enough, compared with 76% in homes built 1965-2001 and 85% in homes built 2002 or later.

There is no clear overall trend by dwelling type with 39% of respondents in flats/maisonettes saying it would not get too warm in winter, compared to 38% in bungalows and 36% in houses.

There is considerable variation with heating system. Respondents who state that it would not get too warm in winter represent 35% of those who identify central heating as their main heating, compared with 23% with district heating, 68% with portable heaters and 45% with heating fixed in individual rooms. In contrast, those with district heating overwhelmingly report always being warm enough (95%), with much lower percentages for those who use portable heating (44%) or heating that is fixed in the room (64%). This suggests problems with control of heating, particularly district heating.

Oddly, the 10% of respondents who say they do not do anything to control the temperature of their home (e.g. by manually turning the heating on or off or by use of a

[2] Base: 1742 cases that provided income data.

thermostat) are less likely to overheat: 50% say it would not get too warm in winter compared with only 35% of those who do in some way control the temperature. Of those who reported not controlling the temperature, 73% saw no need to change the temperature, 22% did not believe they had the means to control it and 6% believed it would increase energy use.

3.3. The role of natural ventilation

To avoid overheating, a key strategy for most households (in winter and summer) is to open windows. This was therefore explored further by asking "For which of these reasons do you sometimes open a window at home?" Almost all households open windows and in most cases, they do so mainly for fresh air (85%) and to keep cool (79%), while 44% of households open windows to let out smoke or smells and 38% to sleep better or to avoid condensation.

Older households (all over 60) are the least likely to open windows for most of the reasons listed. Households with higher income are more likely to open windows, for instance, to keep cool (85% in highest quartile, 75% in lowest quartile), to let out smoke or smells (55% and 37% respectively), to avoid condensation (46% and 33% respectively) or to sleep better (48% and 31% respectively). Owner-occupiers are more likely to open windows to stay cool (82%) or to sleep better (44%) than those that rent from a private landlord (70% to keep cool and 26% to sleep better) or a social landlord (78% to keep cool, 28% to sleep better). This could in principle be due to the dwelling, the household or perhaps where they live (urban/rural or different neighbourhoods).

Unsurprisingly, households that sometimes get too warm in winter are more likely to open windows than those who do not (83% compared to 74%) and the trend is even more pronounced for summer (85% vs 50%). There are no clear trends by age or type of dwelling except that those in a flat/maisonette are less likely to open windows in order to sleep better (28%) compared to those in a bungalow (33%) or house (42%).

There might be times when people would like to open windows to keep cool but are unable to do so. Respondents were therefore asked "Are there ever times when you would like to open a window or door to keep cool, but you don't do it for one of these reasons?" and could choose multiple answers from a list. As Figure 3 shows, a majority of households experience at least one barrier to opening a window. Concern about security is most prevalent barrier (30% of households), followed by noise (24%) and other conditions outdoors (18%). The design or condition of the window itself was a barrier for less than 5% of households.

There is little difference between household types except that households with preschool children are more likely to cite concerns about safety (e.g. to prevent children falling out): 27% compared to households without children where only 4% and 5% give this reason in adult households aged under or over 60 respectively.

Those in the lowest income quartile are more likely to report no barriers to opening windows – 35% compared to 25% in the highest quartile. The main differences are due to noise, other conditions outdoors and to keep pets in (6% difference between lowest and highest quartile in each case). There is little difference in concerns about security among the income quartiles (30% or 31% for all quartiles).

Households in a flat/maisonette do not generally report more barriers to opening windows (31% say this never happens) than those in houses or bungalows (32% and 33% respectively) but are more likely to not open windows due to noise outside. On the other hand, those in a bungalow are more likely to cite concerns about security (37%) than those in flats/maisonettes (29%) or houses (29%). Those renting from a private landlord are more likely to report no barriers (36% compared to 30% of owner-occupiers). There is no clear trend by age of dwelling.

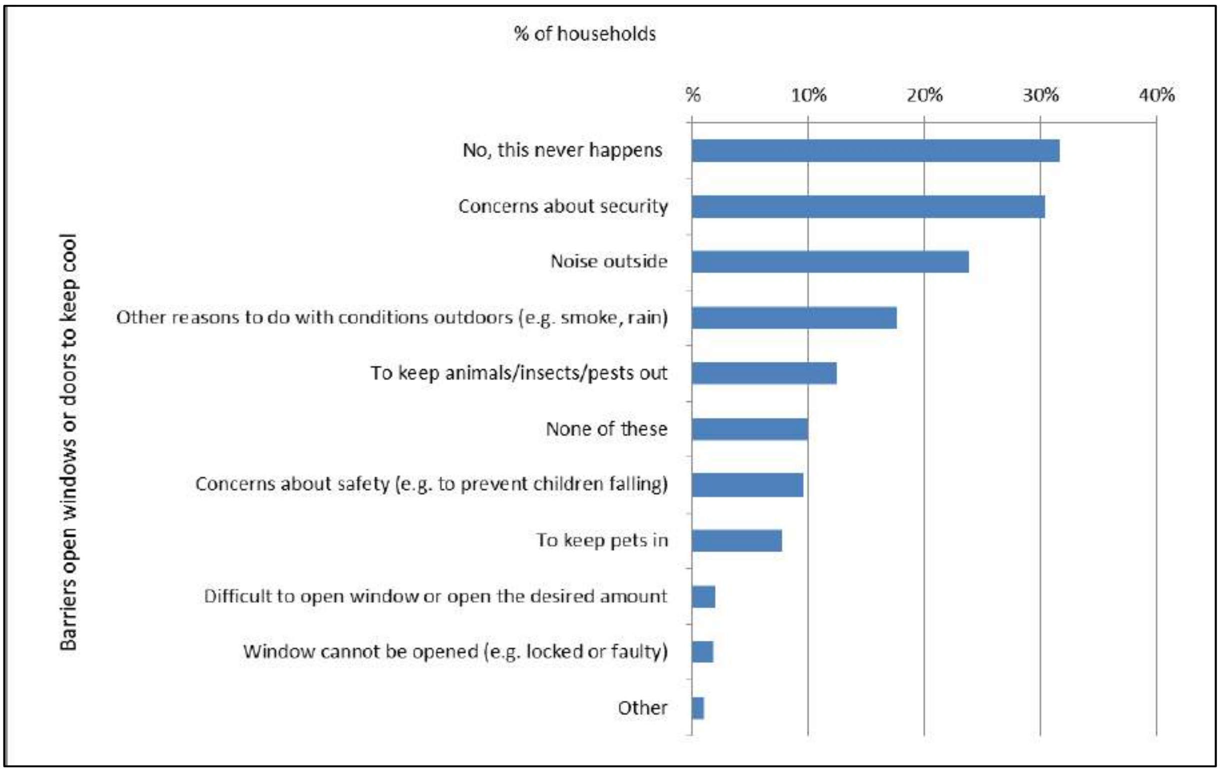


Figure 3 Barriers to opening windows[3]

4. Discussion

Overheating in British homes is widespread in summer and surprisingly common in winter. While winter overheating is likely to manifest mainly in terms of discomfort and impaired sleep and performance, in summer it can be a more serious issue, affecting health and potentially causing fatalities. Current strategies for keeping cool may be sub-optimal from a perspective of comfort and/or energy use. Therefore, throughout the year, and with climate change in mind, it is important to have effective strategies for avoiding overheating. As a starting point, this study has characterised what households currently do and why they do it.

While a dominant means of keeping cool is to open windows (or otherwise use natural ventilation), strategies include a wide range of behaviours and individual households often use multiple means to avoid overheating. It is also apparent that the strategies are not all fixed but rather respond to changes in weather and – to a lesser extent – to other changes (such as someone being unwell or working at home). The strategies include:

- modifying the indoor environment, using heating and cooling systems in addition to the building itself (e.g. shading or windows);
- mitigating the impact of overheating by adapting clothing/bedding, cooling the body the inside (e.g. with a cold drink) or from the outside (e.g. with a fan or shower);
- changing location (within the home or by going elsewhere).

This evidence adds to our understanding of adaptive opportunity in relation to thermal comfort, thus showing how adaptation could be more effective and more widely used by

[3] Base: 2285.

households. Mechanical cooling is rarely used at present and there is merit in understanding and promoting effective strategies that avoid any perceived need for greater use of mechanical cooling in future: mechanical cooling is expensive for households to purchase and use, and – in most cases – adds to carbon emissions.

For example, it is important to be able to open windows. While most households already open windows to keep cool, they do not necessarily do it in the optimum way. Windows may need to be opened with anticipation, before a home overheats, and kept open at night to cool the building fabric. Even if a household understands this, most respondents reported at least one barrier to opening windows, mainly security, noise and other conditions outdoors such as smoke, odours, wind or rain. If such barriers could be addressed, this would facilitate cooling. Security is most relevant when a home is unoccupied or the household is asleep. Large windows offer higher air-change rate but small, secure windows (or mechanical ventilation) allow constant low-level ventilation, including for night cooling. Finally, night ventilation can be made more effective if the home has exposed thermal mass.

The changes required are thus likely to require action not just in relation to windows but the barriers to opening windows, mechanical ventilation and households' understanding of how to avoid overheating. It is also important to take into account, when planning window openings, that opening windows also serve other purposes, notably "for fresh air", to let out smoke or smells, to sleep better or to avoid condensation. In addition, much greater use could be made of solar shading: while most households have internal shading, a minority use it for cooling and few have external shading. Greater application of external shading could perhaps be supported by smart control systems and night ventilation. Many households sometimes go outside the home to keep cool, emphasising the importance of having access to outside space.

In addition to understanding overheating at population level, it is important to understand variations within the population. Older homes (and less well insulated homes) were overall less likely to overheat, suggesting a risk of an increasing overheating problem in future. Older homes were also less likely always to be warm enough in winter. In winter the percentage reporting that it would not get too warm is highest among those whose main heating is portable heaters, followed by those heating fixed in individual rooms, then central heating and district heating. Again this is the inverse of the findings on being warm enough. In fact, across several factors, there was an inverse relationship between always being warm enough and always being cool enough. This suggests a conflict between ability to keep warm and ability to avoid overheating in winter and – therefore – an opportunity both to improve comfort and to save energy through better control of heating, particularly district heating.

There is also variation with dwelling type but it is not entirely predictable. Oddly, those who have part or their entire home on the ground floor are not less likely overall to open windows to keep cool than those that do not live on the ground floor. Flats and maisonettes are generally more likely to overheat than houses or bungalows but probably arising from multiple factors. Generally in the UK, occupants of flats and maisonettes are more likely to:

- have another dwelling above or below, in addition to any to the sides;
- have windows on only one façade;
- benefit from wind and stack effects;
- be located in urban areas;
- not open windows due to noise outside;
- have no security-related barrier to opening windows.

Older households (all over 60) are consistently less likely to report overheating or to take action to avoid it. Effects of age may arise because of age directly (e.g. some kind of mental or physiological change), a cohort effect (i.e. the current generation of older people has had particular life experiences that would not necessarily be repeated in future) or simply because older people have been longer in their current home and therefore understand better how to keep cool there. Overheating also varies in a more complex way with the related factor of household size, but not with whether there is usually somebody at home during the day. The latter finding is perhaps surprising, given that the temperature tends to by higher during the day. However, this may be balanced by being able to open windows (or take other mitigation actions) during the day.

Households with higher incomes, and owner-occupiers, are more likely to need to do something to keep cool but with the net effect that they are less likely to overheat.

Thus, both dwelling and household factors are associated with overheating, emphasising the need to address both housing design and the behaviours by which households avoid overheating. An effective intervention to engage households and bring about change should take into account *Means*, *Motive* and *Opportunity* (Raw *et al* 2010). *Means* is the technology and/or behaviour involved in the change. *Motive* is the reason why households will want to act. *Opportunity* is the resource (e.g. time, space or money) to act. In other words, householders' response to an intervention depends on knowing what to do, having a reason for doing it and having the resources to do it. Therefore, if we understand the motives for cooling behaviour, this should assist with encouraging people to develop effective strategies for keeping cool.

While thermal comfort may be the obvious need met by keeping cool, this study begins to identify examples of broader motives. Raw *et al* (2017) derived five underlying dimensions in relation to heating the home and keeping warm: *Other people, Comfort, Hygiene*, *Resource* and *Ease*. These same dimensions can be seen in relation to avoiding overheating.

- The dimension *Other people* is manifested in how cooling behaviour is affected by the presence of children or visitors, and the need to work from home. Another implication of this dimension is that the more visible changes that might facilitate cooling may need to be managed in relation to self-image. This could include, for example, messages about the potential negative impact of air conditioning and the positive aesthetics of external shading.
- While *Comfort* is clearly a motive for cooling, it can also be a barrier, when window-opening is inhibited by noise or outdoor odours. Furthermore, households use a range of methods used to keep cool, other than cooling the indoor environment. These alternatives should not be characterised merely as compromises for when the home is too warm. Not only can they save money and energy, they can have merit in their own right. For example, dressing in cool clothing in summer can give a sense of relaxation and informality, while reducing the 'thermal shock' of contrast with the temperature outdoors.
- *Hygiene* can be a motive for cooling (e.g. keeping healthy and not sweating) or for particular means of keeping cool (e.g. taking a cool shower). Other aspects of *Hygiene* can represent barriers when window-opening is inhibited by concerns over safety, security or the health effects of outdoor air pollution.
- Regarding the *Resource* dimension, opening a window may be seen as a zero-cost option and, in summer, that may be true, at least for some households. In winter, it can have a cost (financial and environmental) if it represents an alternative to controlling the heating. And some other *Means* do have a cost (e.g. cool drinks, having a cool shower). So *Resource* could be a motive for achieving effective passive cooling, especially compared with the cost (financial and environmental) of air conditioning.

- Habits may be a common consequence of the *Ease* motive. Habits are an essential part of life: without them, we would be overwhelmed by making repeated trivial decisions. So habits are a good thing but not all habits are good, and they can be difficult to change. This is perhaps evidenced by the relatively low incidence of households changing what they do to keep cool as some circumstances vary.

5. Conclusion

Projections of a warmer environment in future entail a dual challenge: to manage the risk of homes overheating and to do so without further contributing to climate warming. This is likely to require changes to management of the outdoor environment, the design of homes, the facilities they incorporate and the behaviour of householders. Given the diversity of current household strategies and the needs that drive behaviour, future strategies for avoiding overheating need to be built on an understanding of what households are currently doing and why they are doing it. Without this understanding, it is possible that future policy may apply means that are technically sound but do not meet the complex needs of different types of household.

References

A more extensive list of the literature reviewed for this project is contained in Raw & Littleford (2014). For reasons of space, those 11 pages of references are not repeated here.

National Centre for Social Research, 2014. *What people need and do that involves heat energy: findings from qualitative research*. Report SSH_SS1501_14 to the Energy Technologies Institute. http://www.eti.co.uk/programmes/smart-systems-heat/consumer-behaviour-study

Raw, G.J. & Littleford, C. 2014. *Consumer Response and Behaviour: literature review*. Report SSH_SS1501_09 to the Energy Technologies Institute. http://www.eti.co.uk/programmes/smart-systems-heat/consumer-behaviour-study

Raw, G.J., Littleford, C. & Clery, E. 2017. Saving energy with a better indoor environment. *Architectural Science Review* 60(3), 239-248. DOI:10.1080/00038628.2017.1300131

Raw, G.J., Varnham, J. & Schooling, J. 2010. *Focus on behaviour change – reducing energy demand in homes.* London, UK: Department for Communities & Local Government. http://www.communities.gov.uk/publications/planningandbuilding/energybehaviourchange

Acknowledgements

This research was commissioned and funded by the Energy Technologies Institute as a part of its Smart Systems and Heat Programme, Work Area 5: Consumer Response and Behaviour (CRaB). The overall objective was to inform the design, development and demonstration of a cost-effective smart energy system, suitable for future roll-out within the UK. CRaB was a partnership of PRP Architects and the Energy Institute at University College London, with NatCen Social Research (NatCen) as subcontractors leading the fieldwork. Statistical analysis reported here was assisted by Sarah Kunz (NatCen, now at UCL).

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Developing user profiles for mixed-mode office buildings operation based on occupant behaviour evaluation

Leticia de Oliveira Neves[1], Eduardo Rodrigues Quesada[2], Camila Anchieta[3] and Karin Soares Chvatal[4]

[1] School of Civil Engineering, Architecture and Urban Design, University of Campinas, Brazil, leticia@fec.unicamp.br;
[2] School of Civil Engineering, Architecture and Urban Design, University of Campinas, Brazil, edu_r_quesada@hotmail.com;
[3] Institute of Architecture and Urbanism, University of Sao Paulo, Sao Carlos, SP, Brazil anchietac@gmail.com;
[4] Institute of Architecture and Urbanism, University of Sao Paulo, Sao Carlos, SP, Brazil karin@sc.usp.br.

Abstract: User profiles can generate discrepancies between the measured and simulated data, when building performance simulation tools provide the latter. Nevertheless, specialized literature observed the inadequacy of using current thermal comfort models to describe occupant comfort in mixed-mode buildings and no specific guidelines are provided in current standards. This paper addresses occupant behaviour within mixed-mode office buildings controlled by occupants, located in a Brazilian humid subtropical climate, with the objective to develop user profiles of operation to be used as input data in computer simulation analyses. Three office rooms operating in a concurrent mixed-mode configuration were investigated in a field research. Indoor climatic measurements monitored the environmental variables (dry bulb temperature, radiant temperature, air velocity and relative humidity) and user control variables (manual operation of the air-conditioning and natural ventilation systems) in situ. Field surveys were simultaneously conducted with the offices' occupants. As a result, occupant behaviour regarding the building's controls is analysed and compared to the static and adaptive thermal comfort models from ASHRAE Standard 55-2013. In conclusion, a user profile to be used as input data for computer simulations is developed, aiming to support more accurate investigations about the thermal and energy performances of mixed-mode office buildings.

Keywords: mixed-mode buildings; occupant behaviour; thermal comfort; field research.

1. Introduction

Mixed-mode ventilation (MMV) is an option that allows to combine natural ventilation and mechanical cooling systems as a possible solution to provide cooling, natural ventilation, Indoor Air Quality (IAQ) and thermal comfort to users (Brager et al., 2000). It is the response of architects, engineers and researchers when faced with the challenge to provide thermal comfort to users while reducing energy use. Albeit a solely naturally ventilated building consumes less energy than a full time air-conditioned one, users do not appreciate the discomfort experienced in such buildings when the climatic conditions are extreme; hence the combination of a mechanical system and natural ventilation to maintain the indoor environment at thermally comfortable levels.

MMV is a relatively new subject; there are no standards for its operation or for its control strategies, even though it is well known that different adaptive behaviours of building inhabitants occur when buildings are heated and cooled or when they are free-running (Nicol, 2017). In addition, there still isn't a complete guide on how to simulate or even design such buildings (Salcido et al., 2016), which makes their modelling in simulation programs a challenging task. Also, MMV allows the user to partially or completely control the environment, and because occupant behaviour is a highly sensitive input parameter in simulations, it can also be a great source of uncertainty. When modelling, most simulation programs provide the possibility to adjust and regulate the simulated environment by altering the building's controls, such as window openings and temperature set points (Andersen et al., 2013). However, discrepancies have been reported between the simulated and measured data, which can lead to inaccurate simulation results (Andersen et al., 2007; Haldi & Robinson, 2008; Schweiker & Shukuya, 2009; Fabi et al., 2013). In an effort to diminish and/or mitigate such discrepancies, field studies have been conducted using field surveys and/or environmental variables monitoring in residential (Rijal et al., 2014; Calì et al., 2016; Jones et al., 2017) and office buildings (Nicol, 2001; Haldi & Robinson, 2009; Rijal et al., 2009). The data collected in such monitoring campaigns, contribute to developing or improving measuring methodologies, or for creating stochastic models of behaviour to be used in simulation programs, among other contributions, all aiming to obtain more accurate results in simulations.

Rijal et al. (2007) conducted an investigation in office buildings in the UK, by means of field surveys and temperature monitoring, regarding window opening behaviour, to create a method to simulate office buildings and include the effects of window opening behaviour on thermal comfort and energy use. D'oca and Hong (2014) applied a statistical analysis technique to a data set collected in offices, to identify the factors that most influenced window opening and closing. In a second stage, the authors used two data mining techniques to identify window operation patterns in the measured data in an effort to obtain distinct behavioural patterns. In the final step, the patterns served as a basis to create association rules to divide the occupants into typical user profiles. Andersen et al. (2013) conducted a study consisting of measurements of occupants' window opening behaviour in residencies. Patterns of behaviour were established according to ventilation type and ownership of the unit. Based on the acquired data set, four models of occupant behaviour patterns regarding the opening and closing of windows were created and proposed to be used in simulation programs, thus increasing the validity of the simulation results.

As stated by Ackerly et al. (2011), there is a need for more field studies in MMV buildings to assess the specific design and operating characteristics that might influence adaptive comfort. Moreover, defining typical behavioural patterns to be implemented in simulation programs is a method that can significantly improve the validity of simulation results (Andersen et al., 2013). This work addresses occupant behaviour within mixed-mode office buildings controlled by occupants, located in a Brazilian humid subtropical climate, with the objective to develop user profiles of operation to be used as input data in computer simulation analyses, in an effort to acquire more accurate results.

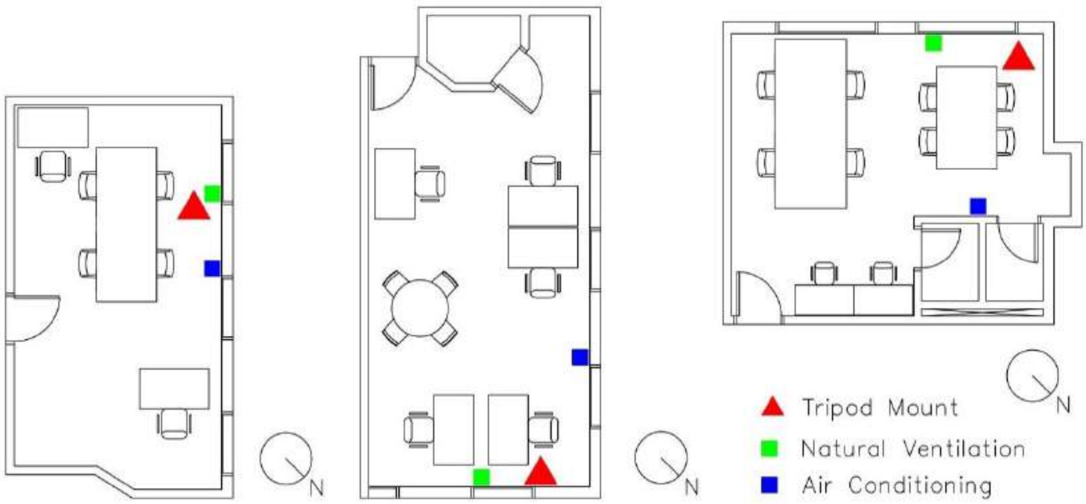
2. Method

Field studies were carried out from April (autumn) to October (spring) 2017 in three office rooms from mixed-mode office buildings located in the city of São Paulo, in the southeast region of Brazil. São Paulo is located at the latitude 23°32' south and altitude 760 m, and is characterized by a humid subtropical climate, with dry winter and hot summer, according to Köppen climate classification (Alvares et al., 2014). The analysis included environmental and user control variables taken in situ and subjective data collected from questionnaires. Details about the study are presented in the following subsections.

2.1. The selected offices

Three office rooms from two office buildings were selected to perform the field monitoring. The selection was based on average values of building height, floor area, office area, and vicinity, taken from a database that contains selected geometry and envelope thermal properties information of 153 mixed-mode office buildings, located in the city of São Paulo (Neves et al., 2017).

Two office rooms (Figure 1a, b) are located in the 4th and 6th floors of a concrete office building and have 25 m² and 33 m² of floor area (Figure 2a). The natural ventilation strategies of the office rooms within this building are single-sided (office room 01) and cross ventilation (office room 02). To control indoor conditions, users are free to manually operate top hung windows (Figure 3a) or turn on self-contained air-conditioning units (Figure 3b). The third office room (Figure 1c) is located in the 4th floor of a concrete office building and has 29 m² of floor area (Figure 2b). The natural ventilation strategy of the office room is single-sided ventilation, provided by manually operated top hung windows and an individual air-conditioning system provided by a split unit (Figure 3c), which users were also free to control at any given time.



(a) Office room 01 (b) Office room 02 (c) Office room 03

Figure 1. Office rooms from field monitoring

(a) Office building – rooms 01 and 02 (b) Office building – room 03

Figure 2. Office buildings from field monitoring

(a) Top hung window (b) Self-contained air-conditioning unit (c) Split air-conditioning indoor unit

Figure 3. Natural ventilation and air-conditioning systems

2.2. Measurements of physical parameters and subjective questionnaires

Indoor environmental variables were taken in situ comprising air temperature, radiant temperature, air velocity, and relative humidity. User control variables were also monitored, including manual operation of the air-conditioning and natural ventilation systems. Outdoor environmental data were taken from a meteorological station located 9 km distant from the buildings (INMET, 2017).

Instruments used to perform the field monitoring are listed in Table 1. A state measure sensor was responsible to measure the window state (closed/opened) and it was placed at the window frame. A set of air temperature/ relative humidity sensor was placed at the air-conditioning indoor unit fins, in order to measure the air-conditioning triggering, which was identified by changes in ambient air temperature. All other equipment were placed on a tripod, at the height correspondent to a standing person (1.2 m). The tripods had to be located next to the windows (Figure 1), even though it is not the best monitoring location, so it would not disturb the occupants. They were, though, protected from direct sunlight.

Table 1. Technical specifications of instruments used during field monitoring

Instrument	Range	Accuracy
Datalogger air temperature/ relative humidity	-20°C to +55°C 0 to 100%	± 0.4°C ± 2%
Datalogger air temperature (for globe temperature)	-35°C to +55°C	±0,5°C
Datalogger air temperature/ air speed	1 to + 20 m/s	± (0.03 m/s + 5%)
Air speed probe	0 to + 10 m/s	± (0.03 m/s + 5%)
Air temperature probe	-50°C to + 125°C	± 0.2°C
Datalogger air temperature/ relative humidity (for air-conditioning triggering monitoring)	-20°C to + 85°C 0 to + 100 %	±0.5°C 0.6 %
State measure datalogger (for window position monitoring)	Maximum frequency 1Hz	± 1 minute per month at 25 ° C

Data acquisition occurred every 15 minutes for indoor environmental variables, every 5 minutes for air-conditioning triggering monitoring and every time a state change was detected, for window opening monitoring. Data collection occurred from April 8th to 16th (autumn), from June 19th to July 3rd (winter) and from October 3rd to 26th (spring).

The field survey was also supported by subjective data collected from questionnaires containing questions about the characteristics of occupants (clothing and metabolic activity) and, as shown in Table 2, questions about thermal comfort (sensation and preference) and possible issues that could interfere with windows operation (noise, air pollution, odour and glare).

Table 2. Data gathered from questionnaires

Question		Answer
Thermal sensation: how do you feel right now about the thermal environment?		-3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), +1 (slightly warm), +2 (warm), +3 (hot)
Thermal preference: would you prefer it to be		-2 (cooler), -1 (slightly cooler), 0 (no change), +1 (slightly warmer), +2 (warmer)
What's your perception about:	Noise from outside	Scale 1 to 7 (from unsatisfactory to satisfactory)
	Air pollution from outside	
	Odour from outside	
	Glare (when blinds are opened)	

2.3. Data analysis

Collected data were organized in spreadsheets, where graphs and tables were generated, considering office work hour from 9 am to 5 pm and excluding weekends and holidays. The 'Thermal Comfort Tool' online calculator from the Center for the Built Environment (CBE, 2017) was used to perform the static (i.e., PMV) and adaptive thermal comfort calculations for each period of measurement, according to ASHRAE 55 (2013). The standard was also used to calculate average results for clothing insulation (clo) and metabolic activities (met) obtained from the field survey, in order to use it for PMV calculations.

User profiles were developed, aiming to support more accurate investigations about thermal and energy performances of mixed-mode office buildings located in the city of Sao Paulo, by using computer simulation. Setpoint ranges defined from gathered data were compared to user profiles from similar studies, set to operate in specific climatic conditions. To that end, MMV studies developed through computer simulation were gathered from current literature.

3. Results and discussion

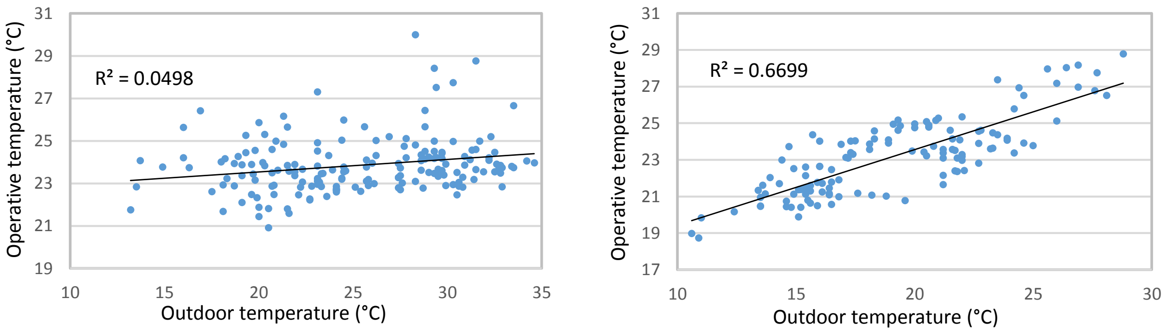
3.1. Indoor thermal environment and mixed-mode operation

Results of the field measurements were compiled and the mean, standard deviation (SD), minimum (Min) and maximum (Max) values for each variable were calculated, considering air-conditioned (AC) and naturally ventilated (NV) periods of operation, as indicated in Table 3. NV periods corresponded to the periods when windows were opened, which was set from the results obtained by the window state monitoring. Besides the fact that mean indoor thermal conditions were quite similar between the AC and NV periods, the NV period showed a wider pattern of variation with outdoor temperature, which is similar to what occurs in free-running buildings. Moreover, regression analyses presented in Figure 4 indicate no correlation between indoor operative temperature and outdoor temperature for the AC period (as expected), but a good correlation for the NV period (R^2 = 0.67). Figure 4 also gives an overview of all collected data.

Table 3. Statistical summary of indoor and outdoor climatic conditions for AC period, NV period and combined data (whole period)

Parameter	AC period (number of hourly data = 176)				NV period (number of hourly data = 126)				Combined data	
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
DBT (°C)	23.9	1.3	21.1	30.2	23.1	2.0	18.8	28.3	23.6	1.7
MRT (°C)	23.8	1.3	20.7	29.8	23.3	2.2	18.7	29.3	23.6	1.7
Top (°C)	23.8	1.3	20.9	30.0	23.2	2.1	18.7	28.8	23.6	1.7
RH (%)	46.3	7.8	32.4	66.5	61.5	9.0	44.9	76.7	52.6	11.2
Tout (°C)	25.3	5.0	13.2	34.6	19.1	4.1	10.6	28.8	22.7	5.6

DBT = dry bulb temperature, MRT = mean radiant temperature, Top = operative temperature, RH = relative humidity, Tout = outdoor dry bulb temperature.



(a) AC period (b) NV period

Figure 4. Outdoor temperatures plotted against indoor operative temperature (Top), for AC and NV periods

In free-running buildings there is substantial seasonal variation of window control probabilities at the same outdoor temperature (Borgeson & Brager, 2008). In order to better characterize seasonal behaviour during field measurements, Figure 5 presents results compiled for each season, for AC and NV periods. Indeed, a higher variation of mean indoor operative temperature can be observed between seasons for the NV periods. Also, NV periods presented a wider range of variation between minimum and maximum temperatures, as expected. In winter, NV temperatures were lower than AC temperatures, since the offices have no heating system (air-conditioning systems are cooling only) and when the outdoor temperatures were low the AC system was off.

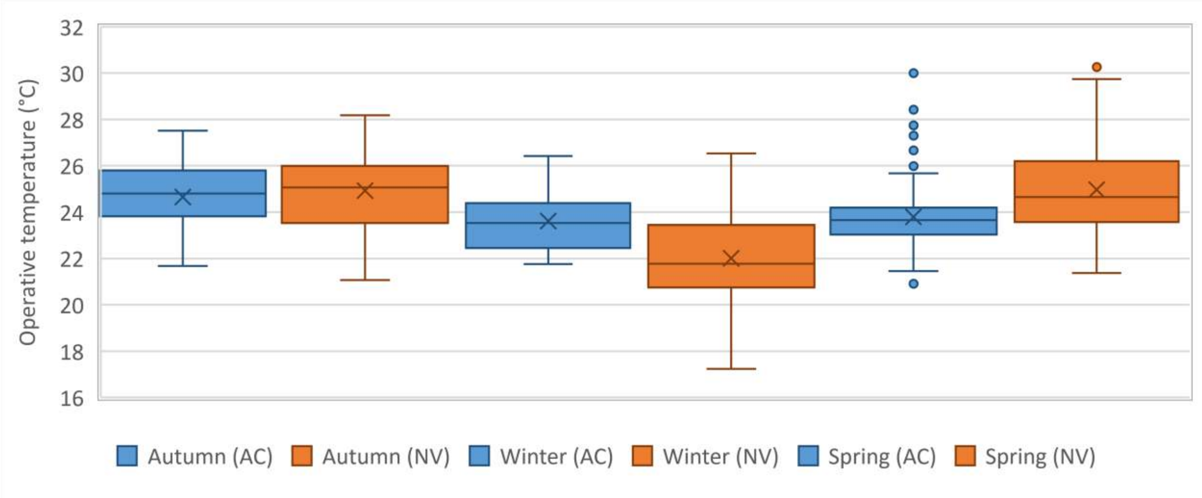


Figure 5. Box plot of operative temperature for AC and NV periods. The line within each box is the median, the cross is the mean, the edges of the box are the 25th and 75th percentiles, the dots are the outliers.

In general, low air velocity was obtained in the measurements, even when windows were opened. The maximum velocity registered was 0.17 m/s. Observations during the field study suggest that these results are due to the fact that office rooms 01 and 03 have single sided ventilation and office room 02, even having the possibility of cross ventilation, is not adequately operated by users in order to make use of it. Similar results were obtained by De Vecchi et al. (2017) for the same type of building in Florianópolis, Brazil. In fact, previous studies affirmed that actions on windows were positively correlated with exterior air temperature, but not with wind speed, as stated by Haldi and Robinson (2009).

A comparison between predicted sensation votes from static and adaptive models (ASHRAE 55, 2013) was performed, showing the second choice to be more applicable to MMV buildings, both when air-conditioning or natural ventilation were being used (Table 4). This result emphasized the inadequacy of using the static model to set thermal comfort conditions in MMV buildings, especially in NV periods, as stated by Deuble and de Dear (2012).

Table 4. Statistical summary of static and adaptive models thermal comfort calculations from field measurements, according to ASHRAE 55 (2013)

Season	Parameter	AC period (number of hourly data = 176)			NV period (number of hourly data = 126)		
		% of compliance with ASHRAE 55-2013	Mean	SD	% of compliance with ASHRAE 55-2013	Mean	SD
Autumn	Static model (PMV)	64	0.17	0.53	14	0.88	0.31
	Adaptive model (Top)	93	24.6	1.6	79	26.5	1.1
Winter	Static model (PMV)	60	0.45	0.28	67	0.29	0.31
	Adaptive model (Top)	100	23.6	1.3	98	22.5	1.5
Spring	Static model (PMV)	90	-0.07	0.36	77	0.33	0.50
	Adaptive model (Top)	98	23.8	1.3	85	25.0	1.9

Predicted sensation votes from field measurements could not be compared to actual votes obtained from questionnaires because the gathered data were not conclusive (there were only 32 valid responses). The mean value obtained from valid answers was 0.4 (between neutral and slightly warm). Nevertheless, similar studies report either the applicability of the adaptive comfort model to MMV buildings (Deuble & de Dear, 2012; Luo et al., 2015) or the possibility of operating in a wider range of indoor temperatures other than that recommended by the adaptive model (Rupp & Ghisi, 2017). Further study is needed to better understand the subject over this specific case.

The occupants from the three office rooms, who personally control windows and air-conditioning units, were asked about their perception about noise, air pollution, odour and glare. The valid responses were gathered during air-conditioned (AC) and naturally ventilated (NV) periods and are shown in Figures 6 to 9. Answers point out air pollution and glare as subjects that should be better investigated, once it could negatively interfere in the naturally ventilated periods. Besides the use of blinds not hindering the opening of windows, it could significantly reduce the airflow.

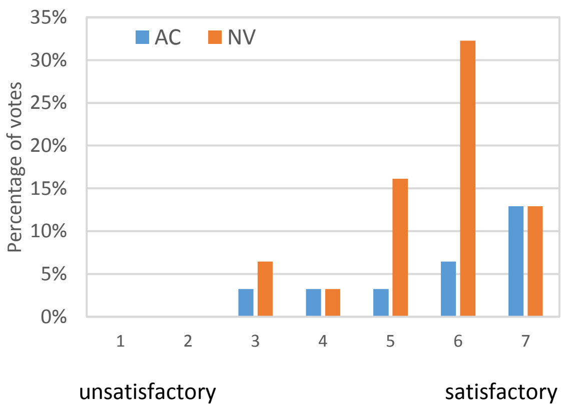


Figure 6. Noise from outside

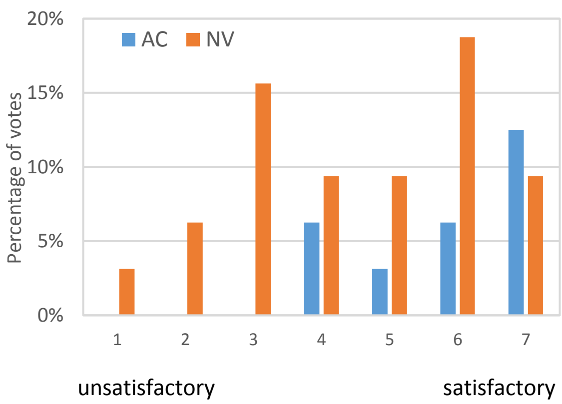


Figure 7. Air pollution from outside

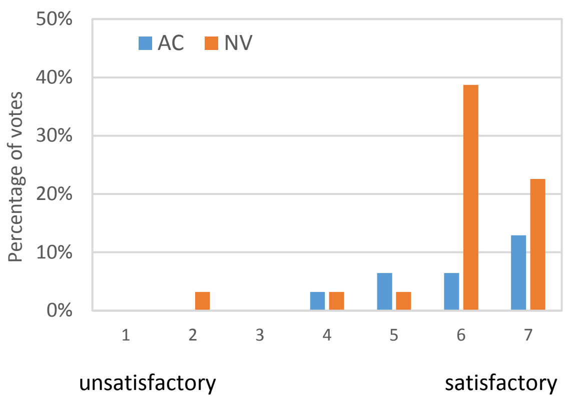


Figure 8. Odour from outside

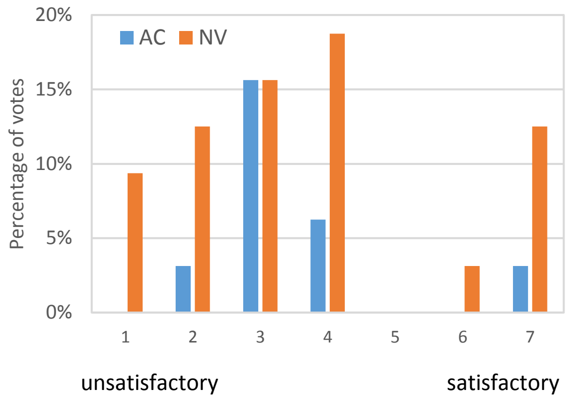


Figure 9. Glare (when blinds are opened)

3.2. User profile setting and comparison to similar researches

Results obtained from field measurements indicate that the use of natural ventilation and air-conditioning controls may be predicted from knowledge of the indoor and outdoor temperatures. Reasons for using both data is that, whilst indoor temperature is an output data in computer simulations, outdoor temperature is an input data. Besides that, according to Borgeson and Brager (2008) models using either of both produce good results. Indoor operative temperature was used in the user profile prediction, since it represents the adaptive model approach. Therefore, a user profile was developed, to be used as input data for computer simulations, based on the mean plus standard deviation values obtained from the statistical summary of indoor and outdoor field measurements, for air-conditioning and naturally ventilated periods. The result is presented in Table 5 (highlighted), together with results from similar investigations in several other countries, in order to draw a comparison.

Table 5. Comparison of the current study with previous studies about MMV on office buildings

Reference	Method	Geographical location	Setpoint range adopted
Wang and Chen (2013)	Computer simulations (EnergyPlus)	Five different cities in USA: Miami, Phoenix, Las Vegas, San Francisco, and Philadelphia.	Natural ventilation: 15°C < Tout < 22°C and Ti > 19°C Air-conditioning: Ti > 24°C (cooling)
Rupp and Ghisi (2013)	Computer simulations (EnergyPlus)	Florianópolis, Brazil	Natural ventilation: Ti > 22°C (winter) and Ti > 20°C (summer) Air-conditioning: Ti > 24°C (cooling)
Bajenaru et al. (2016)	Computer simulations (DesignBuilder)	New Delhi, India	Natural ventilation: Ti > 23°C and Tout < 26°C
Aradag et al. (2011)	Computer simulations (Matlab, Simulink)	Several cities in Turkey	Natural ventilation: Ti > 20°C
Malwaki et al. (2016)	CFD simulations (FloVENT)	Massachusetts, USA	Natural ventilation: Ti ≤ 26.7°C and RH = 60%
Roetzel et al. (2014)	Computer simulations (EnergyPlus)	Hamburg, Germany; Athens, Greece; Alice Springs, Australia	Natural ventilation: setpoint according to upper limits of ASHRAE Standard 55 adaptive comfort model 80% satisfaction
Hu and Karava (2014)	Computer simulations (Matlab, GenOpt)	Montreal, Canada	Natural ventilation: 21°C ≤ Ti ≤ 24°C
Neves et al. (2018)	Computer simulations (EnergyPlus)*	São Paulo, Brazil	Natural ventilation: Top ≤ 25°C and Tout < 23°C Air-conditioning: Top > 25°C and/or Tout ≥ 25°C

* To be developed in a next phase of the current research project

4. Conclusions

Field measurements and surveys were performed in order to predict occupant behaviour regarding the controlling of windows and the air-conditioning system of MMV office buildings located in the city of São Paulo, Brazil. Such predictions are needed to provide user profiles to be used as input data in thermal and energy performance simulation of buildings. The following findings are noteworthy:

- Mean values of indoor variables were quite similar between the air-conditioned and naturally ventilated periods (see Table 3), which shows a similarity of thermal comfort conditions set by users, for both cases. However, the naturally ventilated period presented a wider standard deviation, which means that indoor conditions drifted towards outdoor conditions.
- The adaptive model was more suitable to MMV buildings, both when air-conditioning or natural ventilation were being used, since the percentage of compliance with ASHRAE 55 (2013) was higher (see Table 4). Results also demonstrate the inadequacy of using the static model to set thermal comfort conditions for this type of building.
- Results obtained from window state measurement showed that window use was not predictable and repeatable, which makes building simulation models increasingly complex, when assessing this issue (Ackerly et al., 2011). However, user control schedules currently adopted in computer simulations of MMV buildings frequently do not correspond to what is demonstrated by real people in real buildings (Borgeson & Brager, 2008), which emphasizes the importance of investigating occupant behaviour through field research. Regarding that, our main goal was to create a user profile setting that fits computer simulation studies.
- More field measurements need to be conducted during the summer, for a better understanding of occupant behaviour in different seasons of the year. This issue will be addressed in further steps of this research.

5. Acknowledgments

The authors would like to thank São Paulo Research Foundation (FAPESP) for the financial support. The authors would also like to thank all those involved in the field study.

6. References

Ackerly, K., Baker, L. and Brager, G. (2011) *Window use in mixed-mode buildings: a literature review*. Summary report. USA: Center for the Built Environment, University of California.

Alvares, C. A. *et al.* (2013) 'Köppen's climate classification map for Brazil', *Meteorologische Zeitschrift*, 22(6), pp. 711–728.

Andersen, R. *et al.* (2013) 'Window opening behaviour modelled from measurements in Danish dwellings', *Building and Environment*, 69, pp. 101–113. doi: 10.1016/j.buildenv.2013.07.005.

Andersen, R. V., Olesen, B. W. and Toftum, J. (2007) 'Simulation of the effects of occupant behaviour on indoor climate and energy consumption', in *Proceedings of Clima*. *Clima 2007 WellBeing Indoors*, p. 9th.

Aradag, S. *et al.* (2011) 'Hybrid Ventilation System Simulation for Several Cities in Turkey', *International Journal of Ventilation*, 9(4), pp. 351–357. doi: 10.1080/14733315.2011.11683893.

ASHRAE - American Society of Heating, Refrigerating and Air Conditioning Engineers (2013) *ANSI/ASHRAE 55-2013 - Thermal environmental conditions for human occupancy*. Atlanta, EUA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Bajenaru, N., Damian, A. and Frunzulica, R. (2016) 'Evaluation of the Energy Performance for a nZEB Office Building under Specific Climatic Conditions', *Energy Procedia*, 85, pp. 26–34. doi: 10.1016/j.egypro.2015.12.271.

Borgeson, S. and Brager, G. (2008) *Occupant control of windows: accounting for human behavior in buildingsimulation*. Internal report. USA: Center for the Built Environment, University of California.

Brager, G., Ring, E. and Powell, K. (2000) 'Mixed-mode ventilation: HVAC meets mother nature', *Engineered Systems*.

Calì, D. *et al.* (2016) 'Analysis of occupants' behavior related to the use of windows in German households', *Building and Environment*, 103, pp. 54–69. doi: 10.1016/j.buildenv.2016.03.024.

CBE - Center for the Built Environment (2017) 'Thermal Comfort Tool'. Available at: http://comfort.cbe.berkeley.edu/ (Accessed: 1 December 2017).

De Vecchi, R. *et al.* (2017) 'Thermal comfort in office buildings: Findings from a field study in mixed-mode and fully-air conditioning environments under humid subtropical conditions', *Building and Environment*, 123, pp. 672–683. doi: 10.1016/j.buildenv.2017.07.029.

Deuble, M. P. and de Dear, R. J. (2012) 'Mixed-mode buildings: A double standard in occupants' comfort expectations', *Building and Environment*, 54, pp. 53–60. doi: 10.1016/j.buildenv.2012.01.021.

D'Oca, S. and Hong, T. (2014) 'A data-mining approach to discover patterns of window opening and closing behavior in offices', *Building and Environment*, 82, pp. 726–739. doi: 10.1016/j.buildenv.2014.10.021.

Fabi, V. *et al.* (2013) 'A methodology for modelling energy-related human behaviour: Application to window opening behaviour in residential buildings', *Building Simulation*, 6(4), pp. 415–427. doi: 10.1007/s12273-013-0119-6.

Forgiarini Rupp, R. and Ghisi, E. (2017) 'Predicting thermal comfort in office buildings in a Brazilian temperate and humid climate', *Energy and Buildings*, 144, pp. 152–166. doi: 10.1016/j.enbuild.2017.03.039.

Haldi, F. and Robinson, D. (2008) 'On the behaviour and adaptation of office occupants', *Building and Environment*, 43(12), pp. 2163–2177. doi: 10.1016/j.buildenv.2008.01.003.

Haldi, F. and Robinson, D. (2009) 'Interactions with window openings by office occupants', *Building and Environment*, 44(12), pp. 2378–2395. doi: 10.1016/j.buildenv.2009.03.025.

Hu, J. and Karava, P. (2014) 'Model predictive control strategies for buildings with mixed-mode cooling', *Building and Environment*, 71, pp. 233–244. doi: 10.1016/j.buildenv.2013.09.005.

INMET - Instituto Nacional de Meteorologia (2017) 'Weather station data'. Available at: http://www.inmet.gov.br/portal/index.php?r=estacoes/estacoesAutomaticas (Accessed: 1 December 2017).

Jones, R. V. *et al.* (2017) 'Stochastic behavioural models of occupants' main bedroom window operation for UK residential buildings', *Building and Environment*, 118, pp. 144–158. doi: 10.1016/j.buildenv.2017.03.033.

Luo, M. *et al.* (2015) 'Evaluating thermal comfort in mixed-mode buildings: A field study in a subtropical climate',*Building and Environment*, 88, pp. 46–54. doi: 10.1016/j.buildenv.2014.06.019.

Malkawi, A. *et al.* (2016) 'Predicting thermal and energy performance of mixed-mode ventilation using an integrated simulation approach', *Building Simulation*, 9(3), pp. 335–346. doi: 10.1007/s12273-016- 0271-x.

Neves, L. de O. *et al.* (2017) 'Envelope design of mixed-mode office buildings: theory versus practice', in *Design to Thrive*. *Passive and Low Energy Architecture*, Edimburgh, UK.

Nicol, F. (2017) 'Temperature and adaptive comfort in heated, cooled and free-running dwellings', *Building Research & Information*, 45(7), pp. 730–744. doi: 10.1080/09613218.2017.1283922.

Nicol, J. F. (2001) 'Characterising occupant behavior in buildings: towards a stochastic model of occupant use of windows, lights, blinds heaters and fans', in *Seventh International IBPSA Conference*. *Building Simulation*, Rio de Janeiro, Brazil, pp. 1073–1078.

Rijal, H. B. *et al.* (2007) 'Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings', *Energy and Buildings*, 39(7), pp. 823–836. doi: 10.1016/j.enbuild.2007.02.003.

Rijal, H. B., Humphreys, M. A. and Nicol, J. F. (2009) 'Understanding occupant behaviour: the use of controls in mixed-mode office buildings', *Building Research & Information*, 37(4), pp. 381–396. doi: 10.1080/09613210902904221.

Rijal, H. B., Humphreys, M. A. and Nicol, J. F. (2014) 'Development of a Window Opening Algorithm to Predict Occupant Behavior in Japanese Houses', in *PLEA*. *Passive and Low Energy Architecture*, Ahmedabad.

Roetzel, A., Tsangrassoulis, A. and Dietrich, U. (2014) 'Impact of building design and occupancy on office comfort and energy performance in different climates', *Building and Environment*, 71, pp. 165–175. doi: 10.1016/j.buildenv.2013.10.001.

Rupp, R. F. and Ghisi, E. (no date) 'Potencial de economia de energia elétrica através do uso da luz natural e da ventilação híbrida em edifícios comerciais em Florianópolis', *Ambiente Construído*, 13(4), pp. 75–86.

Salcido, J. C., Raheem, A. A. and Issa, R. R. A. (2016) 'From simulation to monitoring: Evaluating the potential of mixed-mode ventilation (MMV) systems for integrating natural ventilation in office buildings through a comprehensive literature review', *Energy and Buildings*, 127, pp. 1008–1018. doi: 10.1016/j.enbuild.2016.06.054.

Schweiker, M. and Shukuya, M. (2009) 'Comparison of theoretical and statistical models of air-conditioning-unit usage behaviour in a residential setting under Japanese climatic conditions', *Building and Environment*, 44(10), pp. 2137–2149. doi: 10.1016/j.buildenv.2009.03.004.

Wang, H. and Chen, Q. (2013) 'A semi-empirical model for studying the impact of thermal mass and cost-return analysis on mixed-mode ventilation in office buildings', *Energy and Buildings*, 67, pp. 267–274. doi: 10.1016/j.enbuild.2013.08.025.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Managing comfort in low energy housing – the role of gardens, balconies, allotments and greenhouses

Sonja Oliveira[1], Elena Marco[1], Bill Gething[1] and Martin Green[2]

[1] Department of Architecture and the Built Environment, University of the West of England, Bristol, UK
[2] School of the Built Environment, University of Reading, Reading, UK

Abstract: This paper examines management of thermal comfort in a low energy housing development in England drawing on residents', designers' and housing managers' views. Thermal comfort studies have tended to mainly focus on measurement techniques and comfort criteria. There has been little attention devoted to how designers as well as residents account for thermal comfort in the design and management of indoor and or outdoor space. Findings suggest designers and housing managers play a critical role in the conception of interstitial spaces between an individual home, street, garden and collective community landscaping. It was found that whilst equipped with advanced technologies to heat and cool their homes, residents' adaptation strategies to manage discomfort evolved primarily around escaping to a range of individual, ad hoc collective and dedicated community spaces. The importance of outdoor spaces as traditional regimes of cooling is well researched, however an extended understanding of an outdoor environment's spatial and social role for designers and residents in planning and managing comfort is largely unexamined. The analysis also provides a novel method in the studies of thermal comfort – a timely contribution in light of recent questioning of the nature of human interaction with thermal comfort (Nicol and Roaf 2017).

Keywords: architecture, design practice, housing, low energy, thermal comfort

1. Introduction

The purpose of this paper is to examine how residents, designers and housing managers treat indoor thermal comfort/discomfort in a recently built low energy housing development in the UK. Too often views from those who conceive the designed environment (including architects, engineers, planning and sustainability consultants) as well as those who are tasked with managing homes (housing managers) are not taken into account or sufficiently studied in relation to or with residents' views. Residents' experiences and views tend to be the dominant focus in studies of thermal comfort, whether to test existing models, enable new ones or more recently tell 'their stories' (Day and O'Brien, 2017). Research discussing ways to manage thermal comfort have also tended to emphasise either historical expectations of thermal comfort (Shove et al., 2009), the effects of cultural norms (Fennel, 2011), the everyday immediate 'coping' of discomfort through clothing, windows and blinds (Haldi et al., 2010) rather than a continuous process of designing/managing/learning how to 'cope'.

In addition to the socio-technical shaping of approaches to managing comfort, there have been growing studies on residents' use of the technology that is designed to manage indoor comfort including controls, thermostats and smart meters (Stevenson et al., 2013, Peffer et al., 2011). In most studies, the motivation to study residents' approaches to thermal comfort is often driven by a need to explain 'above average' or 'inconsistent' energy use. Studies tend to report a lack of engagement, understanding or usability of the technology such as controls (Stevenson et al., 2013; Gill et al., 2010) on the one hand and social as well as spatial expectations such as 'meanings associated with a home' on the other hand (Devine-Wright et al., 2014). The role of the spatial environment is also mostly studied within the confines of a home focussing on the immediate interaction with windows, blinds and clothing rather than the adjoining transitional context of a street, garden, balcony and community. Exceptions include (though not in a residential context) recent work by Vargas et al., (2017) on role of lobbies and transitional spaces in moderating thermal comfort expectations.

Despite the growing diversity and quantity of academic discussion dedicated to analysing residents approaches to thermal comfort in traditional and low energy homes, few studies examine how diverse users account for thermal comfort within the contexts of their home, street and wider community. The present paper builds on research that views thermal comfort as intertwined with cultural, sensory and spatial factors by examining designers, housing managers and residents approaches in a recently built low energy development in South West England. In particular, the paper is interested in how designers, housing managers and residents approach their 'heated' environment and respond to both delight and difficulties they may encounter. The following sections discuss key approaches within literature on managing thermal comfort. This is followed by an outline of the research methods, findings and discussion. The conclusion reflects upon the policy and practice implications as well as contributions to scholarly work on the topic.

2. Residents managing thermal comfort: fabric, technology, space

Residents' management of thermal comfort is discussed mainly through determining what counts as comfortable for whom (Rupp et al., 2015), predicting frequency and type of comfort adjustment (Kim et al.,2017) and quantifying factors that influence occupant adaptive behaviour (Andersen et al., 2009). Most of the studies draw on quantitative statistical methods with the premise of better or improved prediction of comfort criteria. Where adaptive approach behaviours (as is most commonly referred to) have been studied more closely, focus has been on residents use and interaction with the physical fabric of a home (Hwang and Chen., 2010), active adaptation through clothing (Fuller et al., 2013) or interaction with technology such as controls (Stevenson et al., 2013). An "adaptive approach" is viewed as a response to 'a change' that 'occurs such as to produce discomfort' due to which 'people react in ways which tend to restore their comfort' (Nicol and Humphreys, 2002).

Residents' use and interaction with the physical fabric of a home has been studied mainly with a focus on understanding the drivers for adaptive behaviours including opening windows, drawing blinds or curtains as well as adjusting radiators. Also, most studies tend to highlight the state of the fabric element (such as a window) rather than the transitions of opening and closing (Fabi et al., 2012). Herkel et al., (2008) suggested smaller windows tended to be opened less frequently but once opened were left open for longer, while large windows were opened less frequently and closed after opening. Similarly, Dubrl (1998) found in a large scale European study that types of dwellings (semi detached or detached) influenced the length of time a window stayed open. Hansen et al., (2018) suggested, however, that types of buildings and building characteristics were less influential than clothing particularly in energy inefficient homes. Their study indicates that occupants favoured dressing warmer and keeping lower temperatures in energy-inefficient houses.

Studies on thermal comfort have also been carried out mainly in either indoor or outdoor spatial environments. However, recent work on thermal comfort, though mostly in non-domestic environments, has highlighted the importance and value of analysing spaces between the outdoor and indoor- transitional spaces (Vargas et al., 2017). Transitional spaces are spaces within a building that are also connected with the exterior environment (Kwong & Adam, 2011). These have been variously described as semi-outdoor buffer zones, buffer spaces, in-between spaces, physical links, bridges between the interior and exterior environments, semi-enclosed or half-open spaces (Vargas et al., 2017; Pitts & Bin Saleh, 2007). Together these transition spaces form a hierarchy of microclimates. Pitts and Bin Saleh (2007) suggest whilst also holding an important architectural significance, transitional spaces also can play an important and as yet unexplored role in reducing energy use and thermal comfort 'buffering'. Their research has shown that in moderate climates the length of exposure and the way that spaces are thermally connected can significantly modify thermal perception and preferences in seconds.

2.1 Control of thermal comfort

Studies conducted in energy efficient homes also show at times unexpected results suggesting heating and cooling practices are often associated with diverse user motivations, knowledge and expectations (Eon et al., 2017). Through monitoring ten Australian homes, Eon et al., (2017) noted variations in energy use of over 30%. Differing motivations across individuals living often in the same home affected overall energy use and thermal comfort. Madsen (2017) report in a study of heating systems across three housing types in Denmark on the importance of technologies and material structures shaping heating and cooling practices. A shift in technology from radiators to underfloor heating was found to make a clear difference in both how houses are heated and how thermal comfort is perceived. It is found that changes in material structures of houses consequently change residents' perceptions of comfort and the related everyday practices. A more nuanced set of notions of comfort is suggested in this area of research in relation to different practices such as 'airing and heating practices', as well as the context of seasons and the outdoors.

Residents' management of thermal comfort is also suggested to be dependant amongst many issues, on how users approach their indoor domestic environment particularly in relation to energy efficiency technologies such as controls. Controls and their usability have been a topic of an increasing number of discussions specifically in low energy homes where there may be a number of advanced control technologies installed. In low carbon developments in particular users tend not to make adjustments to controls due to complex technology or unfamiliarity leading to uncomfortable conditions (Bell et al., 2010). In addition, often low carbon developments include separate controls for different services complicating management of homes further (Monahan and Gemell, 2010). For some scholars, key difficulties lie in poor handover practices and often very complex manuals that are difficult to understand (Pett and Guertle, 2004). Stevenson and Rial (2008) suggest difficulties lie in poor knowledge and understanding that can be found across the design team. Discussing the post occupancy survey carried out for the Sigma house, Stevenson and Rial (2008) observe how housing developer's representatives were not always familiar with the more complex controls, referring the user to the induction guide book. Overall, however, less attention is devoted to understanding the activities residents undertake to manage comfort including through engagement with controls in their homes from a qualitative perspective taking into account the spatial, social individual and or collective context.

2.2 Cultural and social concerns in management of thermal comfort

Whilst an established area of research focuses on improving comfort criteria as well as understanding drivers for adaptive behaviour, recent work suggests broader social and cultural issues play a significant role. Fennell's (2011) study of heating enables a greater understanding of the relation between heating and culture, spatialities, technologies, and bodies. In her ethnographic study conducted in Chicago public housing, she finds that heating and comfort are intertwined with class and race dynamics, politics and the bureaucratic regulation of a common sensory regime. Using a similar approach, Cupples et al., (2007) discuss thermal comfort as constituted within national identities and notions of masculinities. Embedded widespread and common practices of using log burners and open fires to heat homes, despite leading to significant air pollution in Christchurch, were found to be deeply tied to notions of 'bearing the cold' and cultural identities linked to the colonial past.

Hards (2013) discusses ways that thermal comfort management practices reflect status and stigma, noting how the adoption of wood-burning stoves defined as 'positional goods' – in the United States in the early 19th century was a form of conspicuous consumption. The argument presented by Hards (2013) suggests that energy consumption and thermal comfort are both a way of conferring status, through conspicuous consumption, or stigma through a person's inability to conform to societal norms with regard to energy consumption. The mobilisation of different forms of capital, including social, economic, cultural and symbolic is found to be important here in both establishing one's status position, but also in avoiding stigma (Hards, 2013). Devine-Wright et al., (2010) suggest that perceptions of cosiness in a home occupied by older adults led to installation of wood burning stoves and fake fireplaces despite the installation of highly efficient low carbon thermal technologies.

A deeper understanding of how cultural factors mediate sensory experiences and practices is believed by some to be crucial for the development of richer understandings of thermal comfort practices, especially in light of common discourses on climate change and energy security (Hitchings and Day, 2011). However, the scarcity of approaches on the experience and attitude towards heat within and outside a 'low carbon home' as well as beyond the systems and technologies that enable it is striking. Whilst the studies discussed in this section of the paper discuss housing and thermal comfort broadly, they enable an important understanding of how heating and comfort are positioned within a wider set of relations between status, stigma (Hards, 2013), national identity and notions of masculinities (Cupples et al., 2007) as well as concepts of cosiness and glow (Devine-Wright et al., 2010).

3. Research design and methods

The research design for this study is based on a visual descriptive case study narrative research approach (Margolis and Pauwels 2011) drawing on multiple data sources including documentary and photographic evidence, observations, semi-structured interviews and focus groups sessions. The research setting is based on a recently built low energy development in South West England consisting of over 185 homes ranging from one-bed flats to five-bed houses (both privately owned and housing association tenanted). The homes were originally designed to be zero carbon in accordance with the UK Level 6 of the

Code for Sustainable Homes (CSH). The heavily insulated homes have a mechanical ventilation system with heat recovery installed as well as a number of other sustainable features such as rainwater harvesting, solar collectors and solar shading. The layout in most homes allows for the kitchen and bedrooms on the ground floor and the living room on the first floor.

3.1 Data collection and analysis

Data collection involved three participant types: residents living in the development, designers and planners involved in the development conception and housing managers whose role involved training, coordination and management of housing association tenants. Discussions with residents took shape over two stages. The first stage included focus group sessions and second stage involved interviews in the residents' homes. Initially 5 focus group sessions were held with resident groups ranging from 6-12 participants. Following the focus group sessions, in-depth semi-structured interviews in 10 homes with 12 participants of diverse ages and backgrounds were held to explore particular aspects that emerged in the focus group discussions. 8 participants who participated in the interviews had also taken part in the focus group sessions. Houses varied from flats, coach houses, 2 bed, 3bed and 5 bed houses located throughout the development. In addition, two homes were shared ownership with the housing association, whereas others were fully privately owned. During interviews, photos were taken during particular discussions of areas within or outside the home that were deemed of interest and particularly relevant to the phenomenon being researched. Focus group sessions and interviews with residents were complemented by interviews with housing association managers, planners and designers. Overall 8 housing management staff and design consultants were interviewed. The research was mindful of ethical issues and was conducted on an entirely confidential, anonymous and consensual basis. See also Table 1 for overview of participant groups and data collection techniques.

Table 1 Overview of participant groups

Type of participant	**Resident**	**Housing manager**	**Design consultant**
Type of data collection technique	Focus groups and interviews	Interviews	Interviews
Number of participants	48 in focus groups and 12 in interviews	3	5

The questions in all the participant sessions (residents, housing managers as well as designers) focused on three key aspects: *background and understanding of expectations and motivations, approaches to the indoor environment in terms of comfort and heat*, *views on control of comfort of indoor environment*. All discussions started with understanding a participants' perceptions of a home, overall views on the drivers for the housing development, reasons for designing, managing or moving to the development and importance placed on the eco ethos of the development. Documentary evidence included design reports, drawings and models of the development as well as any promotional material on the development.

Analysis of the focus group and interview data was informed by thematic analysis (Braun & Clarke, 2006). Data were initially coded into 3 main categories (Background and reasons for designing/managing/moving to development; Experience of designing/managing/living in the development; Views on the indoor thermal environment and how it is adjusted) with more than 30 subcategories; and the main themes presented here stem from a subsequent round of analysis probing issues of heat, control and mitigation strategies as they emerged across the dataset, from which the findings laid out below were drawn. Within each category visual data including photographs of particular house or outdoor garden features were used to contextualise emerging themes and provide an extended understanding into the spatial characteristics of the phenomenon being discussed. Emergent thematic categories included: ***Justifying investment in home design***, ***Role of allotments, balconies and greenhouses*** and ***Community Learning what a home needs***. As reiterated above, the authors are not seeking to generalize from this limited set of cases. Rather the thematic analysis is used to identify some of the key considerations relevant to thermal experience in diverse home settings in a low carbon development, whilst recognizing that these will be manifest differently in other settings.

4. Findings

The findings are discussed across three key 'Managing comfort' themes: ***Justifying investment in home design***; ***Role of allotments, balconies and greenhouses*** and ***Community learning on what the home needs.*** See Figure 1 below.

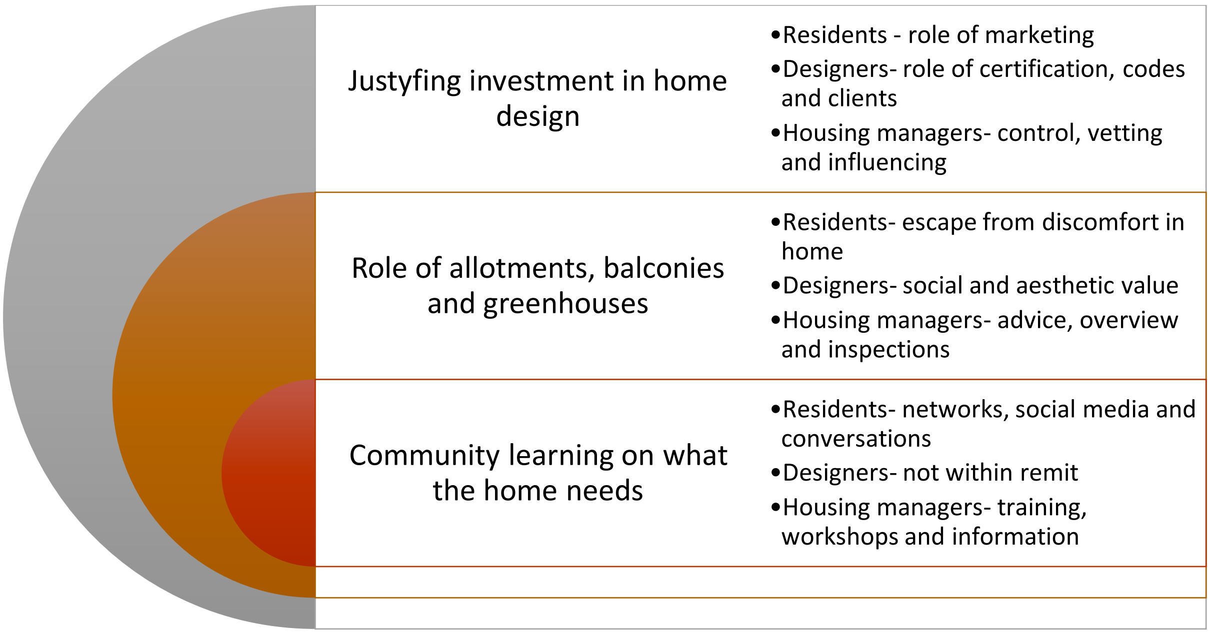


Figure 1 Key analytical categories and themes

In all themes discussions centre around physical and social characteristics of managing thermal comfort (within the home and in the wider development). ***Justifying investment into home design*** involves identifying key problematic areas of the home and justifying the discomfort experienced through reflecting upon appealing characteristics such as 'the kitchen window only this house has', 'the balcony which allows the dog to see out beyond', the 'allotments we never thought we had'. ***Role of allotments, balconies and greenhouses*** includes ways residents, designers and housing managers discuss the role of collective community space for social cohesion on the one hand and as a way to managing and adapting to indoor thermal environments on the other. In most instances homes are found to be too hot, 'controlled by technology' or socially 'isolating' with physical internal or external fabric elements such as such as vents, light switches and balconies, allotments and greenhouses viewed as either opportunities or obstructions to comfort whether indoor or outdoor. Throughout the discussions, the home is described as needing an occupant 'who knows what it needs'. ***Learning what the home needs*** reflects upon ways residents, designers and housing managers discuss the skills and knowledge they perceive a home expects to enable thermal comfort. For the purposes of this paper and due to restrictions in length, two of the main themes are discussed further in sections below.

Justifying investment in home design- Residents, Housing managers and Designers

In most cases residents interviewed found the development by chance; in magazines, portals or local adverts whether moving from elsewhere in the country or elsewhere within the city. In many cases residents chose to live in the development in order to be save money; seeing the key attraction of the homes in promoted low running costs. In some cases, residents were drawn to the advertised 'sense of community' and in some cases the eco features promoted in the sales leaflets such as 'rainwater harvesting', 'solar panels' or 'recycling'. In most cases residents were moving from conventional homes located within a street and had never lived in an estate type development or a new build home.

Whilst most residents did not choose to live in the development because of its low carbon credentials, many were drawn to the idea of a 'created community'. Residents, having described how they moved to the development would often begin to discuss features of their home or development that were unexpected or disappointing. One participant chose her particular home because it had a kitchen window on the corner, allotments nearby and a balcony 'so the dog could watch people come and go'. However, she was to find a type of community (her home was close to what she described as 'the social housing bit') she did not expect and a home which she felt she 'did not have what it needed' in terms of 'knowing what to do and how to use it'.

> *"I had'nt quite realised the impact of living here as there is quite a lot of drama; sometimes its like living in the middle of Eastenders with the bailiffs, police, paramedics, fire engines. You can get them all in one night, all outside my own house…"*

Despite being disappointed the participant goes on to justify the fact the home is invested in already (emotionally as well as financially) by reflecting upon the 'community as being lovely and a microcosm of the country' as well as observing how 'a home is somewhere you have to love' reminding us of the fact her house has 'lots of light and that extra kitchen window; a corner window'.

Designers mostly discussed their motivations or expectations of the development through limitations set out by either the developer client, certifications or codes. One of the participants suggested that the design had undergone many changes in order to meet developers' skills capability whilst also satisfying's very particular code and certification technical requirements:

> *"…we simplified the design of the homes radically because we were trying to build a very high technical standard, higher than developer X had built, and probably higher than they've built since actually, and so we were anxious that the homes were going to be physically changeable or being constructed to meet the technical requirements…"*

Housing managers on the other hand, discussed their expectations as being driven primarily by the lifestyle choices needed of future tenants. One of the housing managers responded how there was an explicit strategy to distance the development from a "hippy commune" and instead provide the facilities of living a low carbon lifestyle:

“…a development that would facilitate people to live very low carbon lifestyles without necessarily being overtly eco, so we weren’t establishing a hippy commune if you like, and the homes, the garden, the landscape, the facilities within the landscape – and the homes as well – if you like quietly provide all the facilities that one might need in order to live a low carbon life…”

The role of balconies, allotments and greenhouses

The role of a collective outdoor space seemed key amenity for many residents, housing managers and designers. This seemed to be prioritised above the home itself with a greater emphasis given to bringing people together rather than gardens as somewhere to retreat to. However, for residents the community spaces were not only spaces for recreation and social gathering as intended by designers but also spaces where ‘problems’ found in the homes could be shared and solved and where the ‘hot’ home could be escaped. For most of the residents, balconies, allotments and greenhouses were described as spaces to ‘escape to’ from ‘hot homes’ as well as spaces within which ‘ideas on how to manage a home’ can be found. One of the residents describes how she struggled with setting up the controls and boiler systems, finding the home consequently dry and hot most of the year not just in the winter. The greenhouse area was a space she could informally walk to and find residents to ask for assistance or advice.

“…I have like most people struggled with the timer; the boiler; I didn’t get any training…my neighbour has struggled as well; it was too hot; because we have such good glazing- it gets very dry hot…I have a greenhouse as well; ive never grown anything and I thought id just try it…and I love it its pleasant there; its my thing; and you get to know everybody who has a greenhouse; you can wonder down there and there are people there; they know what to do with the systems so you learn…”

For the designers, the community spaces were an important non-standard feature that would set the development apart (aesthetically and socially) . After describing how the design team have worked with the developer across the country which has led to a good working relationship, a participant designer described how there were many ways that the developer “had to deviate substantially from their standard approach”. Here it seems that the landscaping team and the building design team had to collaborate more-so than on previous projects in order to develop a physical and social community led space.

“…the original idea, and the one that was maintained across the project was the idea to use the landscape to be able to build the community so it worked at the macro level by providing all the community might need from allotments to compost recycling areas to play areas to larger open fields and meadows and orchards...”

When describing what was important for housing managers in housing more generally, the main role of landscaping was perceived as adding value to the overall site by providing an external shared space.

“…adding value and I don’t mean that in financial terms, albeit they often translate into financial value, but more that the value that well designed landscape can bring to supporting communities and community values by offering external spaces that communities can meet each other in...”

For housing managers, achieving the low carbon lifestyle was not only set by a “technically motivated brief”, but also a ‘spatially managed’ one. By shifting introducing balconies, greater control (not reliant on technology) could be enabled by residents.

> *“…I was very concerned about a design that relied on technology to control the environment so we (the designers and housing managers) introduced the veranda space as a deep overhang, the natural shading that that provides, and the active shading that’s introduced through the shutters across the windows to try and enable people to control that...”*

5. Discussion and conclusion

Extending Shove’s argument (Shove et al., 2009), findings in this paper similarly suggest a need to analyse the dynamics of thermal comfort as intertwined with and through different aspects of everyday life in the home, but also as suggested in this paper in the spaces that adjoin it. The study reported in this paper highlights the significance physical and social spaces inside and outside the home play in residents management of thermal comfort. The question of how placement, use and spatial relations of physical/social spaces and places such as balconies, allotments and greenhouses motivate behavioural learning or adaptation is one that is revealed and will require further study. It has been established for some time in anthropology that the built environment can hold repositories for social meaning, physical bodily orientations and identities (Fennell, 2011). In addition, research in the built environment has observed detailed relationships between comfort and clothing (Cupples et al., 2007), furnishings and openings (Raja et al., 2001; Nicol, 2001). This study extends this work by highlighting how the use of interstitial spaces such as balconies and collective spaces and places such as allotments and greenhouses within and outside the home obstruct or enable management of thermal comfort in low carbon homes.

Within UK policy, the concept of a zero or low carbon house has been (re)defined several times. Currently, three elements are required for a house to be classified as low carbon: 1) the energy demand must be reduced to comply with the Fabric Energy Efficiency Standard (FEES); 2) any remaining carbon emissions must be below the Carbon Compliance Level; and 3) any remaining carbon emissions must be offset through investment in Allowable Solutions projects such as offsite renewable energy sources (ZCH, 2014). Missing are broader implications of spatial and social components of interstitial and outdoor spaces that a home connects to and within which it is situated. Instead too often the focus is on the technological components of heating systems such as valves, controls, thermostats or boiler inaccessible technology and users lack of preparedness or understanding. Further research is needed to better understand the ways physical and social components of a home environment (both inside and outside) help shape how thermal comfort is approached, controlled or ignored. There are implications in this paper on designers of both homes as well as the environment that surrounds them (the gardens, landscaping and parking) and the potential importance they play in the way decisions on comfort and heating in particular are made by residents.

In addition, this paper offers a multidimensional perspective on thermal comfort. Occupants’ experiences and views tend to be the dominant focus in studies of thermal comfort, whether to test existing models, enable new ones or more recently tell ‘their stories’ (Day and O’Brien, 2017). The ability to find different temperatures acceptable depends on the access to opportunities to modify conditions such as the ability to change clothing or activity level which will enable individuals to be more comfortable (Cole et al., 2008). Those opportunities may also be found in the collective spaces and places, in the social realm and within different understandings of the role communities play. Building upon Nicol and Roaf's (2017) call for more strategic and practical 'advice for designers', this study suggests greater care and involvement of all stakeholders is needed in planning and designing interstitial spaces not only as areas for social cohesion (Bhatti, 2006), thermal buffering (Vargas et al., 2017) but also as spaces for collective thermal comfort management learning and coping.

6. References

Andersen, R. V., Toftum, J., Andersen, K. K., & Olesen, B. W. (2009). Survey of occupant behaviour and control of indoor environment in Danish dwellings. *Energy and Buildings*, *41*(1), 11-16.

Braun, V., & Clarke, V., (2006), Using thematic analysis in psychology, *Qualitative Research in Psycholology*, 3, 77–101.

Bell, M., Wingfield, J., Miles-Shenton, D., and Seavers, J., (2010), *Low carbon housing: Lessons from Elm Tree Mews, York:* Joseph Rowntree Foundation.

Bhatti, M. (2006) ''When I'm in the garden I can create my own paradise': Homes and gardens in later life', *Sociological Review*, 54(2), 318-341.

Cole, R. J., Robinson, J., Brown, Z., & O'shea, M. (2008). Re-contextualizing the notion of comfort. *Building Research & Information*, *36*(4), 323-336.

Cupples, J., Guyatt,V., and Pearce,J.,(2007) "Put on a jacket, you wuss": cultural identities, home heating, and air pollution in Christchurch, New Zealand, *Environment and Planning,* 39, 1: 2883- 2898.

Day,K and O'Brien,W (2017) Oh behave! Survey stories and lessons learned from building occupants in high performance buildings, *Energy research and social science*, 11-20

Devine-Wright, P., Wrapson, W., Henshaw, V., & Guy, S., (2014)., Low carbon heating and older adults: comfort, cosiness and glow, *Building Research & Information*, *42*(3), 288-299.

Dubrul,C (1998), Technical note AIVC 23, *Inhabitant behavior with respect to ventilation – A summary report of IEA* Annex VIII

Eon, Christine, Gregory M. Morrison, and Joshua Byrne (2017) "The influence of design and everyday practices on individual heating and cooling behaviour in residential homes." *Energy Efficiency*, 1-21.

Fabi, V., Andersen, R. V., Corgnati, S., & Olesen, B. W. (2012). Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment*, *58*, 188-198.

Fennell, C. (2011), 'Project heat' and sensory politics in redeveloping Chicago public housing, *Ethnography*, *12*(1), 40-64.

Fuller, S., & Bulkeley, H. (2013). Changing countries, changing climates: achieving thermal comfort through adaptation in everyday activities. *Area*, *45*(1), 63-69.

Gill, Z. M., Tierney, M. J., Pegg, I. M., & Allan, N. (2010), Low-energy dwellings: the contribution of behaviours to actual performance, *Building Research & Information*, *38*(5), 491-508.

Hansen,A., Gram-Hanssen, K and Knudsen,H,(2018), How building design and technologies influence heat- realted havits, *Building Research and Information*, 46,1

Haldi, F., & Robinson, D. (2010). Adaptive actions on shading devices in response to local visual stimuli. *Journal of Building Performance Simulation*, *3*(2), 135-153.

Hards, S (2013), Status, Stigma and Energy Practices in the Home, *Local Environment,* 18 (4): 438 - 54. Herkel,S., Knapp,U and Pfafferott, J (2008) Towards a model of user behaviour regarding the manual control of windows in office buildings Build Environ, 43, pp. 588-600

Hitchings, R., & Day, R. (2011), How older people relate to the private winter warmth practices of their peers and why we should be interested, *Environment and Planning A*, *43*(10), 2452-2467.

Hwang, R. L., & Chen, C. P. (2010). Field study on behaviors and adaptation of elderly people and their thermal comfort requirements in residential environments. *Indoor air*, *20*(3), 235-245.

Kim, J. W., Yang, W., & Moon, H. J. (2017). An integrated comfort control with cooling, ventilation, and humidification systems for thermal comfort and low energy consumption. *Science and Technology for the Built Environment*, *23*(2), 264-276.

Jie Kwong, Q., & Adam, N. M. (2011). Perception of thermal comfort in the enclosed transitional space of tropical buildings. *Indoor and Built Environment*, *20*(5), 524-533.

Madsen, L. V. (2017). Materialities shape practices and notions of comfort in everyday life. *Building Research & Information*, 1-12.

Margolis, E., & Pauwels, L. (Eds.). (2011). *The Sage handbook of visual research methods*. Sage. Monahan, S. and Gemmell, A. (2011), *How occupants behave and interact with their homes. The impact on energy use, comfort, control and satisfaction.* NF 35. Amersham: NH BC.

Nicol, J. F., & Roaf, S. (2017). Rethinking thermal comfort., *Building Research and Information*, 45,7 Nicol,J.F and Humphreys,M (2002), Adaptive thermal comfort and sustainable thermal standards for buildings, Energ Build, 34, pp. 563-572

Nicol, J.F., (2001), Characterising occupant behaviour in buildings: towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans. In *Proceedings of the seventh international IBPSA conference*

Peffer, T., Pritoni, M., Meier, A., Aragon, C., Perry, D. (2011), How people use thermostats in homes: A review, *Building Environment*. 46, pp. 2529-2541.

Pett J and Guertle P. (2004), *User behaviour in energy efficient homes* –Phase 2 report. London

Pitts, A., & Saleh, J. B. (2007). Potential for energy saving in building transition spaces. *Energy and Buildings*, *39*(7), 815-822.

Raja, I.A., Nicol, J.F., McCartney, K.J. and Humphreys, M.A., (2001), Thermal comfort: use of controls in naturally ventilated buildings, *Energy and Buildings*, *33*(3), pp.235-244.

Rupp, R. F., Vásquez, N. G., & Lamberts, R. (2015). A review of human thermal comfort in the built environment. *Energy and Buildings*, *105*, 178-205.

Shipworth, M. (2000) *Motivating Home Energy Action: A handbook of what works*, Australian Greenhouse office.

Shove, E., Chappells, H., & Lutzenhiser, L. (Eds.) (2009), Comfort in a lower carbon society. London: Taylor and Francis

Stevenson, F., and Rial, H. (2008) Paper 595: The Sigma Home towards an authentic evaluation of a prototype building. In: *PLEA 2008 –25thConference on Passive and Low Energy Architecture, Dublin*

Stevenson, F., Carmona-Andreu, I., & Hancock, M. (2013). The usability of control interfaces in low-carbon housing. *Architectural Science Review*, *56*(1), 70-82.

Vargas,G, Lawrence,R and Stevenson, F (2017), The role of lobbies: short term thermal transitions, Building Research and Info, 45,7,759-782

Zero Carbon Hub (ZCH) (2014), Design as Built Performance End of Term Report, Zero Carbon Hub

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Seeing is Believing, or is it? An assessment of the influence of interior finish characteristics on thermal comfort perception at a University campus in a temperate climate

Jansen Foo[1] and Anna Mavrogianni [1]

[1] UCL Institute for Environmental Design and Engineering (IEDE), The Bartlett School of Environment, Energy and Resources (BSEER), The Bartlett Faculty of the Built Environment, University College London (UCL)

Abstract: Being a 'condition of mind', thermal comfort can be considered to be both a physiological and psychological response. Research shows that other than the physiological factors which are well established in prevailing thermal comfort standards, behavioural and psychological factors equally affect how humans adapt to the thermal conditions of their environment. Human response to thermal conditions is often based on predispositions associated with their perception and expectations of the physical environment. This paper examined the impact of interior finish characteristics on thermal comfort perception in learning spaces by analysing thermal comfort perceptions of students across 48 lecture theatres surveyed during the winter and spring season between 2012 and 2015 in University College London. A taxonomy of interior finish characteristics was first developed to guide the classification of the lecture theatres into different groups for statistical analysis. Results from hypothesis testing found small yet statistically significant differences in thermal comfort as a function of the colour hues (Δ = 0.1) as well as the perceived naturalness (Δ = 0.06) of interior finish characteristics. The findings of this study may have potential implications for the interior design of low carbon and healthy buildings that aim to minimize energy used for space heating whilst maintaining high indoor thermal comfort.

Keywords: Thermal comfort, Interior finish characteristics, Lecture theatres, Statistical hypothesis tests, Psychological thermal comfort adaptation

1. Introduction

The notion that thermal comfort is a condition of mind that expresses satisfaction with the thermal environment is widely accepted in the current research paradigm (ASHRAE 2013). Based on extensive research of how physical and personal variables, such as air and radiant temperature, air velocity, relative humidity, metabolic rate and clothing levels, affect human thermal comfort, existing codes and standards such as the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 55 (ASHRAE 2013) and the ISO 7730 Standard (ISO 2005) prescribe a precise band of universally applicable thermal comfort temperatures and conditions (Hejis et al. 1998). These standards are based on the heat balance model, which describes how the human thermoregulatory system maintains optimum body temperature through heat production and exchange with the environment (Fanger 1970; ASHRAE 2013). Such universal application often requires the introduction of mechanical heating or cooling systems in order to achieve indoor thermal comfort (Chappells et al. 2005). This is unsurprising as the aim of traditional thermal comfort research was to guide the design of engineered systems (Healey et al. 2012). In the face of current challenges posed by a warming climate, however, the way we design and manage buildings requires a rethink in order to simultaneously mitigate and adapt to climate change whilst enhancing people's health and wellbeing.

A large and growing body of research indicates that not only *physical* and *physiological* factors, but also *sociocultural* and *psychological* factors may affect thermal comfort (Hejis et al. 1998; Parsons 2003). The adaptive thermal comfort model, which is mainly applied to free running buildings, recognises that past thermal experiences, cognitive expectations, cultural background and other individual factors can appreciably influence occupant thermal comfort satisfaction (Brager & de Dear 1998; Humphreys et al. 2016). Studies have shown that by incorporating occupant control, the adaptive model enables thermal comfort to be achieved over a wider range of temperatures (Brager et al. 2004) as the positive emotion conjured by having control over a space is comforting itself (Cohen et al. 1986). The lesson drawn from such research is that thermal comfort is a dynamic phenomenon that encompasses psychological, social and cultural factors.

1.1. Seeing is believing, or is it?

The way people perceive and respond to the conditions of their immediate physical environment is often based on past experiences and accumulated knowledge stored in their memory (Gregory 1970). Those experiences shape a person's expectations. It is shown that emotions associated with sensations that one experienced in a physical space would form part of one's personal memory (Poppelreuter 2012), and the physical design characteristics of a space have been shown to impact on people's mental state. Architects and designers have long capitalized on place related memories by using colour, material, texture, architectural form and other design elements in attempts to evoke spatial experiences, which in turn induce varying emotions and moods (Holl et al. 2006; Pallasmaa 2005; Ritterfeld & Cupchik 1996; Roessler 2012). For example, lower ceiling heights may create a more intimate and relaxing mood compared to higher ceilings, which are perceived as indicative of formal spaces (Alexander et al. 1977). Similarly, shiny surfaces are found to be more stimulating compared to matte surfaces, which are perceived to be more calming (Augustin 2009).

Being a 'condition of mind', thermal comfort could be seen as a both physiological and psychological response (Rohles 2007). However, the relationship between the physical design features of indoor spaces and perceived thermal comfort is seldom explored in the current research paradigm. This knowledge gap is partly addressed by this study, which explores the relationship between interior finish characteristics and thermal comfort in learning environments. To achieve this, self-reported thermal comfort responses of students across 48 lecture theatres surveyed during winter and spring months between 2012 and 2015 in University College London (UCL) were analysed in relation to the interior finish characteristics of the surveyed spaces.

2. Psychological factors in thermal comfort

It is widely acknowledged that physical factors, such as air temperature, mean radiant temperature, air velocity, relative humidity, and personal factors, such as clothing level and metabolic rate, contribute to the heat balance of a human body and influence thermal comfort (de Dear et al. 2013). Existing literature shows that to achieve thermal comfort, human adaptive behavioural, physiological and psychological processes also come into play, of which the impact of psychological processes are least explored. People perceive their physical environment differently and their responses to a physical stimulus or particular situation depend on accumulated knowledge stored within their memory (Gregory 1970). Psychological factors, such as experiences, expectations, naturalness and perceived control can influence the thermal perception and evaluation of a space (Rajapaksha 2017; Nikolopoulou & Steemers 2003; de Dear et al. 1997; Auliciems 1981).

Past experiences shape people's expectations of their thermal environment, which in turn affect how they respond to thermal environmental conditions (Willey 1987). An individual's adaptation level and choice of action to cope with changes in the thermal environment depends on past exposures, thermal history and experiences (Wohlwill 1974). Removing clothing and consuming a cold drink on a hot day or putting on extra clothing before getting out of a building to get into the car on a cold winter day are all decisions made according to the memories and understanding of past experiences. Those experiences could be the unpleasant feelings of warm and cold discomfort on a hot and cold day respectively.

Expectation predisposes people to perceive their thermal environment by what they think it should be like rather than what it really is (Nikolopoulou et al. 2001). Often, this is influenced by past thermal experiences (Auliciems 1981). The predisposition that people have of how they feel the environment should be like influences their thermal perception ultimately (Nikolopoulou & Steemers 2003). For example, people from warm climates would be more inclined to expect variations in thermal conditions in a free running building and more prepared to accept higher indoor temperatures (Fanger & Toftum 2002). Such expectations predispose people psychologically on the thermal sensation they think they would feel once they enter those spaces, thus prompting subsequent actions to cope with the anticipated thermal conditions (de Dear et al. 1991).

Naturalness of indoor spaces is defined as inclusion of natural elements or the replication of processes and places of nature (e.g. flowing streams, forests, etc.). The degree of naturalness of an environment has been found to impact the thermal perception of users (Nikolopoulou et al. 1999; Hirashima et al. 2016; Rajapaksha 2017). In particular, it has been shown that people are more likely to tolerate a wider range of thermal conditions in environments with a higher degree of perceived naturalness (Eliasson et al. 2007).

The availability of either actual or perceived occupant environmental *control* has also been found to increase thermal satisfaction in both air conditioned and free running buildings (Nicol & Humphreys 2002; Brager et al. 2004; Fountain & Brager & de Dear 1996; Mors et al. 2011; de Dear et al. 2013).

2.1. Physical design characteristics of a space and their impact on thermal comfort

There is currently limited knowledge as to how much the physical design characteristics of a space impact thermal comfort perception. Key findings of previous studies on the effects of physical design characteristics on thermal comfort perception are summarized in Table 1. The studies indicate that the physical design characteristics of a space such as interior design, colour hues and presence of natural elements like plants may potentially affect people's perceived thermal comfort. However, the majority of these studies were conducted in controlled laboratory conditions; there is a lack of larger scale studies in real world settings that capture a wide range of interior finish characteristics.

Table 1. Summary of findings from previous studies

Study	Study indicated that psychological factors may have impacted results	Key findings
Rohles et al. (1976)	Yes	Subjects felt warmer in a room finished with natural materials, timber wall panels, red textured carpet and 'warm' lighting.
Ohta et al. (2007)	Yes	Subjects had higher body temperature and felt more thermally comfortable and relaxed in a room with natural elements, such as timber wall panels and Japanese paper.
Fanger (1977)	Neutral	Subjects prefer a lower ambient temperature (0·4°C) under red lighting compared to blue lighting.
Huebner et al. (2016)	Yes	Results support the hue-heat hypothesis as subjects felt more thermally comfortable and warmer in 'warm' light conditions.
Berry (1961)	Neutral	Subjects did not feel more thermally comfortable under "warm" lighting but perceived the coloured lights they experienced according to the hue-heat hypothesis
Bennet (1972)	Neutral	Results on whether wearing coloured goggles have an effect on judgement of temperature was ambiguous. The author speculated that the light effect of the goggles may have confounded the results.
Kobayashi et al. (1992)	Yes	Subjects felt warmer under lower colour temperature (warm-coloured) lights.
Mangone et al. (2014)	Yes	Presence of plants in the space contributed to subjects feeling more thermally comfortable and relaxed.
Qin et al. (2014)	Yes	Subjects were more thermally comfortable, relaxed and showed more satisfaction with the physical environment in spaces with plants.

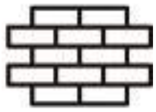
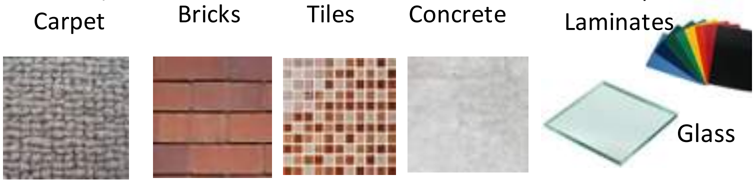
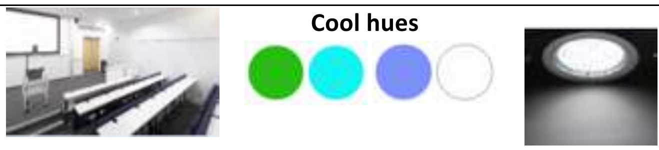
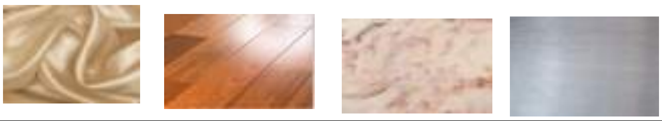
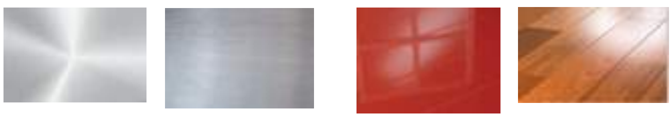
3. Methods

An existing dataset comprising questionnaire surveys of occupant thermal comfort in UCL lecture theatres was used for this study. A taxonomy of interior finish characteristics developed based on factors identified during the literature review was used to organize the surveyed lectures theatres into different groups. Next, statistical analysis and hypothesis testing were performed on the thermal comfort dataset to determine if significant differences exist between lecture theatres with different interior finish characteristics.

3.1. Taxonomy of interior finishes

To guide the classification of UCL lecture theatres for statistical testing, a taxonomy of interior finish characteristics was proposed. Building on previous studies (Berry 1961; Rohles et al. 1976; Fanger 1970; Fanger 1973; Fanger et al. 1977; Kobayashi et al. 1992; Nikolopoulou et al. 1999; Candas et al. 2005; Ohta et al. 2007; Mangone et al. 2014; Qin et al. 2014; Hirashima et al. 2016; Huebner et al. 2016; Rajapaksha 2017), the interior finish characteristics include: i) naturalness, ii) colour hue, iii) texture and iv) sheen. Table 2 illustrates the proposed taxonomy.

Table 2. Taxonomy of interior finish characteristics

Characteristic	Grouping (with examples shown)	Relevant studies
 **Naturalness**	**Natural materials**  **Timber** **Stone** **Straw** **Heavily processed human-made materials** Fabrics/ Carpet, Bricks, Tiles, Concrete, Plastics/ Laminates, Glass 	Rohles et al. (1976); Ohta et al. (2007); Mangone et al. (2014); Qin et al. (2014); Nikolopoulou et al. (1999); Hirashima et al. (2016); Rajapaksha (2017)
 **Colour hue**	**Warm hues**  Warm lighting **Cool hues**  Cool lighting	Fanger et al. (1977); Berry (1961); Candas et al. (2005); Huebner et al. (2016); Kobayashi et al. (1992)
 **Texture**	**Smooth texture**  **Rough texture** 	Rohles et al. (1976); Ohta et al. (2007);
 **Sheen**	**Gloss**  **Matte** 	Rohles et al. (1976); Ohta et al. (2007); Fanger (1970); Fanger (1973)

3.2. Data collection process and sampling method

The surveys were conducted by MSc Environmental Design and Engineering students at the UCL Institute for Environmental Design and Engineering, The Bartlett, in the context of the Methods of Environmental Analysis module coursework during winter (October to

November) and spring (January to March) months between 2012 and 2015. Table 3 shows a summary of the data collection statistics. There is a total of 52 different lecture theatres in the dataset, however, not all lecture theatres were included in the data collection exercise every year. A convenience sampling method was adopted where the selection of subjects was not governed by any specific criteria. Lecturers were contacted in advance in order to obtain their agreement prior to conducting the surveys. Each questionnaire survey was conducted at different days and times in each lecture theatre during the course of an ongoing lecture (typically ranging between 1 and 3 hours). The average response rate was 74% across lecture theatres and survey periods.

Table 3. Summary of data collection statistics

Year	Total number of lecture theatres	Total capacity of all lecture theatres	Total number of students present in lecture theatres	Total number of responses	Average response rate	Date range of data collection	Average duration of survey
2012	38	4081	2223	1756	79%	3 Feb – 22 Feb	1.8 hours
2013	36	3568	1919	1434	75%	28 Jan – 21 Feb	2.0 hours
2014 (1st half) (1H)	41	4645	2216	1810	82%	10 Feb – 10 Mar	1.8 hours
2014 (2nd half) (2H)	46	5255	2907	2146	74%	27 Oct – 30 Nov	1.8 hours
2015	37	4285	3940	2599	80%	28 Oct – 26 Nov	1.7 hours
Total			13205	9745	74%		

Figure 1 shows the locations of the 52 lecture theatres. Data from 4 lecture theatres in the UCL Bentham house* were not considered in this study as the lecture theatres were undergoing refurbishment works and could not be accessed for physical verifications of their interior finishes.

* Bentham B01 Main LT; Bentham B11 Seminar Room 4; Bentham B31 Denys Holland LT; Bentham SB01 Seminar Room 3

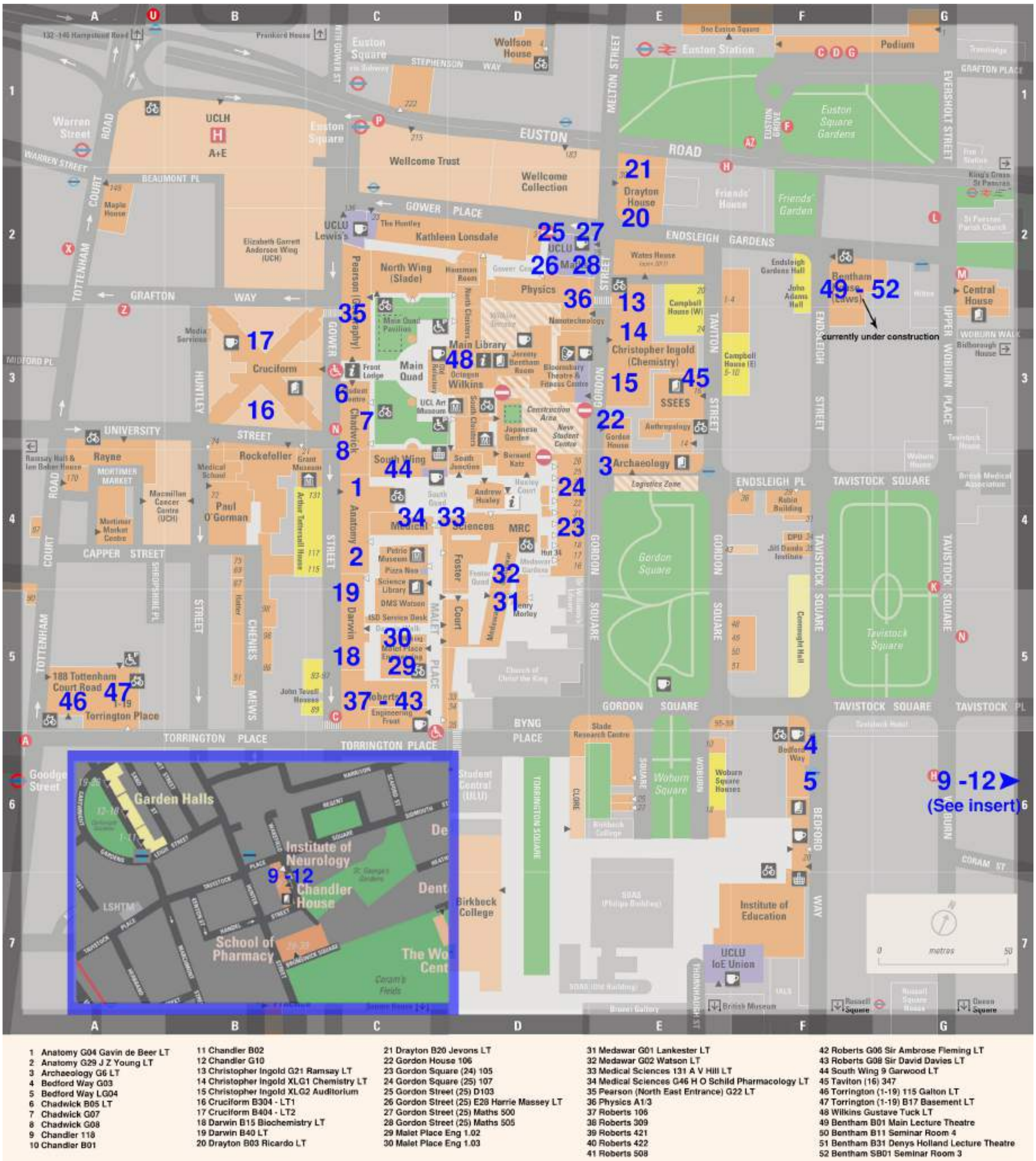


Figure 1. Locations of lecture theatres across UCL campus

Figure 2 shows examples of the interior finish characteristics of the 48 lecture theatres involved in this study.

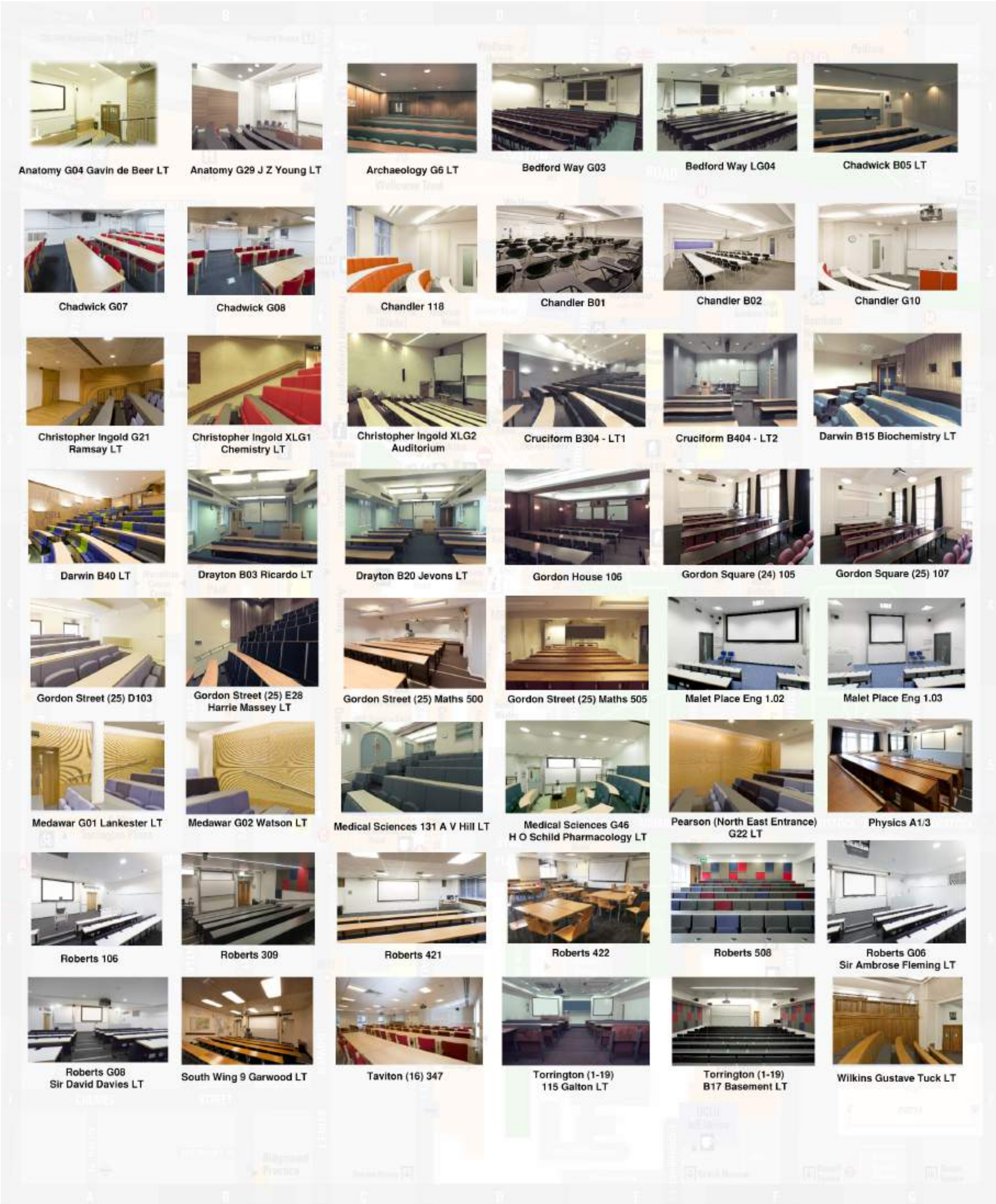


Figure 2. Examples of interior finish characteristics of lecture theatres

The lecture theatre surveys consisted of two components:

- HOBO data loggers were used to measure dry bulb temperature and relative humidity (Onset HOBO U12-02 with accuracy for temperature measurements ± 0.35 °C and ± 25% for relative humidity) at varying intervals (5 to 10 minutes) in the lecture theatres throughout the duration of an ongoing lecture.

- Self-administered questionnaires were handed out to all students present in each lecture theatre. They contained a series of questions on how the students rated the following parameters in the specific lecture theatre:
  - i) thermal comfort (using ASHRAE scale 1 = cold to 7 = hot);
  - ii) visual comfort;
  - iii) acoustic comfort;
  - iv) indoor air quality;
  - v) ergonomics of furniture;
  - vi) ability to concentrate;
  - vii) availability of thermal set point control;
  - viii) basic design;
  - ix) accessibility;
  - x) maintenance;
  - xi) quality of facilities such as electrical sockets, internet access etc.

The students were also invited to indicate their seating position in the questionnaire after completing the survey.

3.2. Classification of lecture theatres

For the purpose of statistical analysis, the lecture theatres were grouped according to their interior characteristics (naturalness of materials; colour hue; texture; sheen). A lecture theatre was assigned a particular characteristic if that characteristic applied to the largest proportion of its surface areas. The lecture theatres were grouped as follows:

1) **Naturalness**
   Group 1: Lecture theatres with interior finish of natural materials, such as timber, stone etc.
   Group 2: Lecture theatres with heavily processed human-made materials, such as concrete, plastic laminates etc.

Darwin B40 with natural timber interior finish

Roberts 106 with heavily-processed materials

Figure 3. Examples of different material interior finishes

2) **Colour hue**
   Group 1: Lecture theatres with interior surface finishes of warm hue colours.
   Group 2: Lecture theatres with interior surface finishes of cool hue colours.

Darwin B40 with mainly warm hues

Roberts 106 with cool hues

Figure 4. Examples of different interior colour hues

3) **Texture**
   Group 1: Lecture theatres with interior surface finishes of smooth texture.
   Group 2: Lecture theatres with interior surface finishes of rough texture.

Christopher Ingold building G21 Ramsay LT with smooth parquet floor and vinyl laminate table tops

Christopher Ingold building XLG1 Chemistry LT with carpeted floor, fabric seats and textured wall finish

Figure 5. Examples of different interior textures

4) **Sheen**
   Group 1: Lecture theatres with gloss interior surface finishes.
   Group 2: Lecture theatres with matte interior surface finishes.

Wilkins Gustave Tuck LT with glossy panels and table tops

Anatomy G29 J Z Young LT with matte interior

Figure 6. Examples of different degree of sheen

3.3. Statistical analysis and hypothesis testing

The quantitative data collected from the surveys were statistically analysed using Microsoft Excel 2016 installed with Analysis ToolPak add-in (Microsoft 2017). Two stages of statistical hypothesis testing through Student's t-tests and single factor Analysis of Variance (ANOVA) tests were carried out to examine potential relationships between thermal comfort levels and interior finish characteristics.

For the first stage, a series of unpaired, two tailed Student's t-tests were performed for the following pairs of hypotheses (null hypothesis, H_0 and alternative hypothesis H_1):

1) **Naturalness**

   $\boldsymbol{H_0}$**:** There is no difference in occupant thermal comfort levels between lecture theatres with interiors with natural materials and lecture theatres with heavily processed human-made materials.

   $\boldsymbol{H_1}$**:** There is a difference in occupant thermal comfort levels between lecture theatres with interiors with natural materials and Lecture theatres with heavily processed human-made materials.

2) **Colour hues**

   $\boldsymbol{H_0}$**:** There is no difference in occupant thermal comfort levels between lecture theatres with interiors of warm hues and lecture theatres with interiors of cool hues.

   $\boldsymbol{H_1}$**:** There is a difference in occupant thermal comfort levels between lecture theatres with interiors of warm hues and lecture theatres with interiors of cool hues.

3) **Texture**

   $\boldsymbol{H_0}$**:** There is no difference in occupant thermal comfort levels between lecture theatres with interiors with smooth textures and lecture theatres with interiors with rough textures.

   $\boldsymbol{H_1}$**:** There is a difference in occupant thermal comfort levels between lecture theatres with interiors with smooth textures and lecture theatres with interiors with rough textures.

4) **Sheen**

   $\boldsymbol{H_0}$**:** There is no difference in occupant thermal comfort levels between lecture theatres with interiors with gloss surface finish and lecture theatres with matte surface finish.

   $\boldsymbol{H_1}$**:** There is a difference in occupant thermal comfort levels between lecture theatres with interiors with gloss surface finish and lecture theatres with matte surface finish.

The aim of the statistical tests was to explore any statistically significant differences in thermal comfort between the groups of different interior finish characteristics. The significance level for the tests was set at 0.05 or 5%.

For the second stage, the interior finish characteristics with t-test results for which the null hypothesis was rejected were further analysed using single factor ANOVA tests. In these tests, the lecture theatres were reclassified into multiple groups of interior finish characteristics.

As the lecture theatre surveys were carried out with the students seated and facing the front of the lecture theatre where the lecturer and projector screen are, the interior surfaces that are predominantly in the students' effective visual field would be the walls of the lecture theatre and the table tops. Figure 7 shows an example of a lecture theatre visual field. As such, the finish characteristics of the walls and table tops may influence the thermal comfort perception of the students. The ANOVA tests would explore whether there are any significant differences between thermal comfort perception and different combinations of surface finish characteristics of the lecture theatre walls and table tops. For the naturalness of interior finish materials, the lecture theatres were classified into the following four groups for the ANOVA test:

i) Natural walls / Natural table tops
ii) Natural walls / Heavily processed human-made table tops
iii) Heavily processed human-made walls / Natural table tops
iv) Heavily processed human-made walls / Heavily processed human-made table tops

The null hypothesis (H_0) and alternative hypothesis (H_1) are:

***H*₀**: There is no difference in occupant thermal comfort levels in lecture theatres with different combinations of natural and heavily processed wall and table top materials.

***H*₁**: There is a difference in occupant thermal comfort levels in lecture theatres with different combinations of natural and heavily processed wall and table top materials.

For colour hue, the lecture theatres were classified into separate groups with the following interior finish characteristics:

i) Warm coloured wall / Warm coloured table top
ii) Warm coloured wall / Cool coloured table top
iii) Cool coloured wall / Warm coloured table top
iv) Cool coloured wall / Cool coloured table top

The null hypothesis (H_0) and alternative hypothesis (H_1) are:

H_0: There is no difference in occupant thermal comfort levels in lecture theatres with different combinations of wall and table top colours.

H_1: There is a difference in occupant thermal comfort levels in lecture theatres with different combinations of wall and table top colours.

Figure 7. Example of visual field of a student seated in a LT

4. Results

4.1. T-test results

The results of the two-tailed Student's t-tests for the hypotheses outlined above for naturalness, colour hue, texture and sheen are presented below.

1) Naturalness

Table 4 shows the two-tailed t-test results on thermal comfort perception between lecture theatres with natural materials and heavily processed human-made materials.

Table 4. t-test results for thermal comfort and naturalness of materials

Grouping	Number of votes (N)	Mean thermal comfort vote	Std Dev	df	$t_{statistic}$	p	Reject null hypothesis?	Effect size
Natural materials	**4186**	**4.109**	**1.194**	**9761**	**2.378**	**0.0174**	**Yes (p≤0.05)**	**0.05**
Heavily processed human-made materials	**5577**	**4.052**	**1.179**					

***H_0*:** There is no difference in occupant thermal comfort levels between Lecture theatres with interiors with natural materials and lecture theatres with heavily processed human-made materials.
***H_1*:** There is a difference in occupant thermal comfort levels between lecture theatres with interiors with natural materials and Lecture theatres with heavily processed human-made materials.

From the results, the null hypothesis can be rejected at 5% significance level. Hence, there is a statistically significant, albeit very small (Δ = 0.06), difference between occupant thermal comfort in lecture theatres with natural material finish and lecture theatres with heavily processed human-made material finish.

2) Colour hue

Table 5 shows the two-tailed t-test results on thermal comfort perception between lecture theatres with cool hues and warm hues.

Table 5. t-test results for thermal comfort and colour hues

Grouping	Number of votes (N)	Mean thermal comfort vote	Std Dev	df	$t_{statistic}$	p	Reject null hypothesis?	Effect size
Cool hues	**7211**	**4.053**	**1.178**	**9761**	**-3.336**	**0.000854**	**Yes (p≤0.05)**	**0.08**
Warm hues	**2552**	**4.144**	**1.214**					

***H_0*:** There is no difference in occupant thermal comfort levels between lecture theatres with interiors of warm hues and lecture theatres with interiors of cool hues.
***H_1*:** There is a difference in occupant thermal comfort levels between lecture theatres with interiors of warm hues and lecture theatres with interiors of cool hues.

From the results, the null hypothesis can be rejected at the 5% significance level. Hence, there is a statistically significant small difference (Δ = 0.1) between occupant thermal comfort in lecture theatres with cool hues and lecture theatres with warm hues.

3) Texture

Table 6 shows the two-tailed t-test results on thermal comfort perception between lecture theatres with smooth and rough textures.

Table 6. t-test results for thermal comfort and different textures

Grouping	Number of votes (N)	Mean thermal comfort vote	Std Dev	df	$t_{statistic}$	p	Reject null hypothesis?
Smooth texture	**3628**	**4.075**	**1.202**	**9761**	**-0.074**	**0.941**	**No (p>0.05)**
Rough texture	**6135**	**4.077**	**1.164**				

***H_0*:** There is no difference in occupant thermal comfort levels between lecture theatres with interiors with smooth textures and lecture theatres with interiors with rough textures.
***H_1*:** There is a difference in occupant thermal comfort levels between lecture theatres with interiors with smooth textures and lecture theatres with interiors with rough textures.

From the results, the null hypothesis cannot be rejected at the 5% significance level. For the examined sample, the difference in user thermal comfort in lecture theatres with smooth textured interior finishes and those with rough textured interior finishes characteristics were negligible and not statistically significant.

4) Sheen

Table 7 shows the two-tailed t-test results on thermal comfort perception between lecture theatres with gloss and matte finish.

Table 7. t-test results for thermal comfort and different interior sheen

Grouping	Number of votes (N)	Mean thermal comfort vote	Std Dev	df	$t_{statistic}$	p	Reject null hypothesis?
Gloss	**2050**	**4.067**	**1.204**	**9761**	**0.411**	**0.681**	**No (p>0.05)**
Matte	**7713**	**4.079**	**1.184**				

H_0**:** There is no difference in occupant thermal comfort levels between lecture theatres with interiors with gloss surface finish and lecture theatres with matte surface finish.

H_1**:** There is a difference in occupant thermal comfort levels between lecture theatres with interiors with gloss surface finish and lecture theatres with matte surface finish.

From the results, the null hypothesis cannot be rejected at the 5% significance level. In other words, the observed (small) difference in user thermal comfort in lecture theatres with gloss interior finish characteristics and lecture theatres with matte interior finish characteristics may be due to chance.

4.2. ANOVA test results

Based on the results of the t-tests in the section above, single factor ANOVA tests were carried out to further explore whether there are any significant differences between thermal comfort perception and the various degrees of *naturalness* and *colour hue* of the lecture theatre walls and table tops. The results of the single factor ANOVA tests are presented below.

1) Naturalness

The significance level for the test is set at 0.05 or 5%. Table 8 shows the results of the ANOVA test for the varying degrees of naturalness.

Table 8. ANOVA table for thermal comfort and different interior material characteristics

SUMMARY						
Groups	*Count*	*Sum*	*Average thermal comfort vote*	*Variance*		
Natural wall / Natural table top	**919**	**3569**	**3.88**	**1.26**		
Natural wall / Heavily processed table top	**1356**	**5417**	**3.99**	**1.60**		
Heavily processed wall / Natural table top	**3135**	**12917**	**4.12**	**1.40**		
Heavily processed wall / Heavily processed table top	**3573**	**14583**	**4.08**	**1.37**		
ANOVA*						
Source of Variation	*SS*	*df*	*MS*	*F*	*p-value*	*F critical*
Between Groups	**47.36**	**3**	**15.79**	**11.28**	**2.33×10^{-7}**	**2.61**
Within Groups	**12610.47**	**8979**	**1.40**			
Total	**12657.83**	**8982**				

* SS: sum of squares; df: degree of freedom; MS: mean square; F: F statistic

From the ANOVA results, the null hypothesis can be rejected at the 5% significance level. Hence, there is a significant difference in occupant thermal comfort in lecture theatres with different combinations of wall and table top materials.

2) Colour hue

Table 9 shows the results of the ANOVA test for colour hue.

Table 9. ANOVA table for thermal comfort and different interior colours

SUMMARY						
Groups	*Count*	*Sum*	*Average thermal comfort vote*	*Variance*		
Warm coloured wall / Warm coloured table top	**1345**	**5406**	**4.02**	**1.45**		
Warm coloured wall / Cool coloured table top	**1402**	**5431**	**3.87**	**1.42**		
Cool coloured wall / Warm coloured table top	**3267**	**13418**	**4.11**	**1.37**		
Cool coloured wall / Cool coloured table top	**2942**	**12111**	**4.12**	**1.41**		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*p-value*	*F critical*
Between Groups	**67.53**	**3**	**22.51**	**16.07**	**$2.13x10^{-10}$**	**2.61**
Within Groups	**12561.67**	**8952**	**1.40**			
Total	**12629.1992**	**8955**				

From results, the null hypothesis can be rejected at the 5% significance level as p-value is less than 0.05. Hence, there is significant difference between occupant thermal comfort in lecture theatres with different combinations of wall and table top colours.

4.3. Distribution of temperature and relative humidity across all lecture theatres

Figures 8 and 9 demonstrate the distribution of the average, minimum and maximum temperatures; and relative humidity (RH) of the lecture theatres (from 2015 to 2012) examined, respectively. Whilst temperature distributions vary across lecture theatres, such differences are not statistically significant in their majority. The only lecture theatre for which there is a significant difference compared to other lecture theatres is Chandler B02.

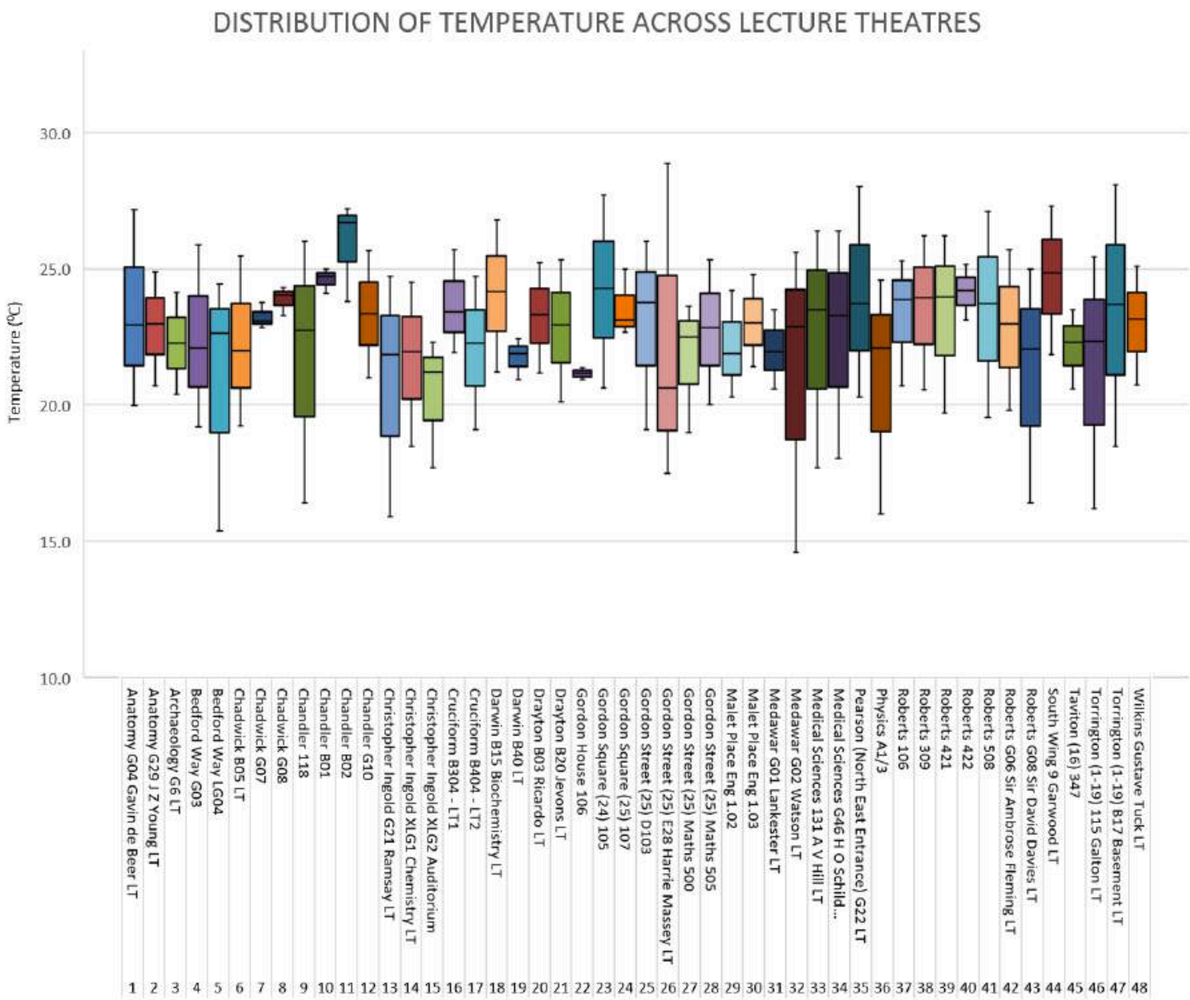


Figure 8. Box plot of temperature distribution across lecture theatres

Unlike the distribution of temperature, the spread of RH across the lecture theatres is much wider. The significant differences between the RH of the lecture theatres may affect the student's thermal comfort levels in the different lecture theatres.

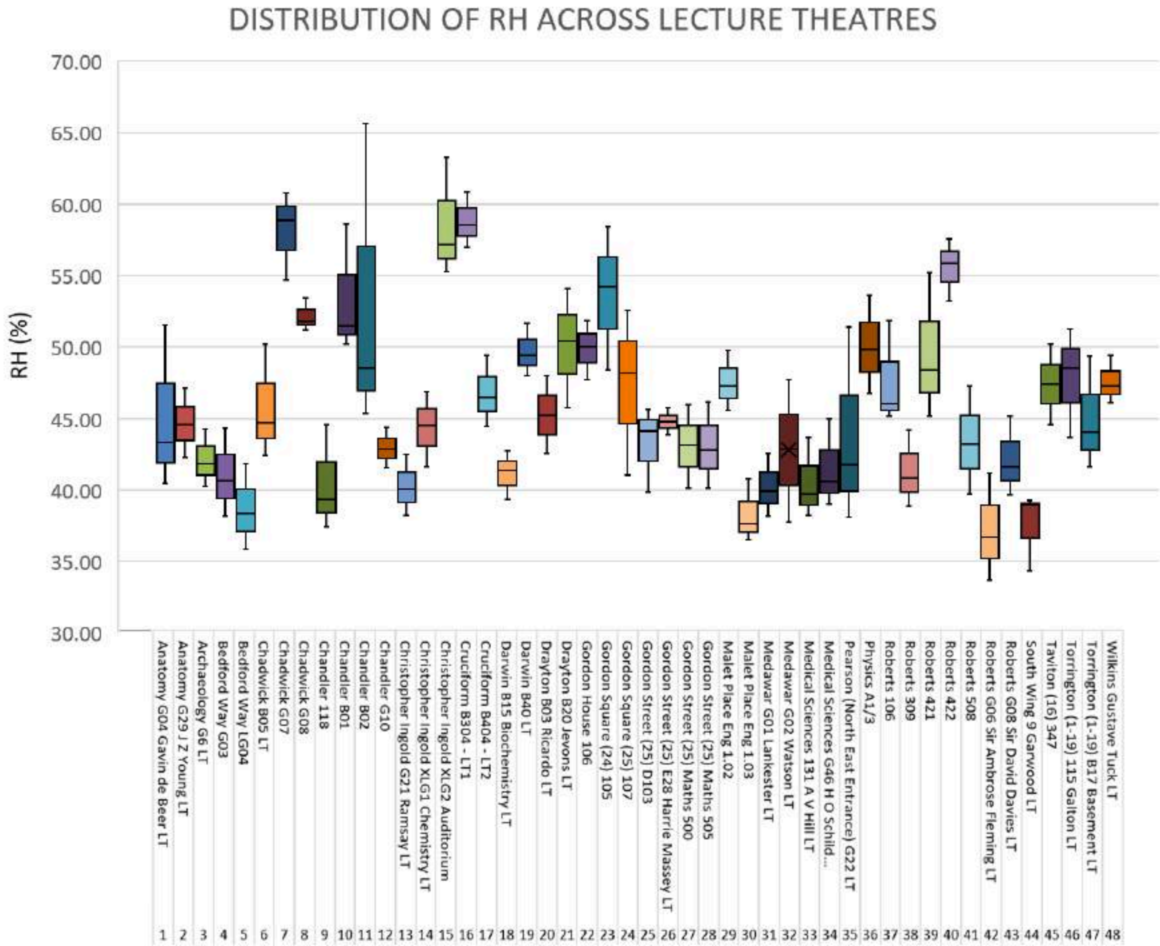


Figure 9. Box plot of RH distribution across lecture theatres

5. Discussion

Statistical hypothesis testing using t-tests was carried out to examine the impact of interior finish characteristics, such as naturalness of materials, colour hue, texture and sheen on thermal comfort perception. A potentially interesting relationship was found between thermal comfort perception with the interior finish characteristics of colour hue and degree of naturalness of materials. Further analysis through ANOVA tests affirmed the potential relationship within the existing dataset although the observed differences are small and the direction of the relationship still slightly unclear. This finding is, nevertheless, in line with earlier studies (Rohles et al. 1976; Ohta et al. 2007; Huebner et al. 2016; Qin et al. 2014), which have suggested that interior finish characteristics, such as naturalness of materials and colour hue, may have potential psychological effects on occupant thermal comfort perception.

Interestingly, further statistical analysis through ANOVA tests also found statistically significant differences and a potential relationship between thermal comfort perception and different combinations of lecture theatre wall and table finish characteristics. However, a closer examination of the average thermal comfort votes for the respective combinations produced contradictory observations, which are in contrast with some of the studies reviewed. For example, in line with the 'hue-heat' hypothesis, one would expect lecture theatres with both warm coloured walls and warm coloured table tops to have a higher average occupant thermal comfort vote closer to the warm side of the thermal sensation scale. However, the results (see Table 9) show that the average thermal comfort vote for lecture theatres with warm coloured walls and table tops was only 4.02 compared to an average of 4.12 for lecture theatres with cool-coloured walls and table tops. Similarly, in the ANOVA test for degree of naturalness of materials, one would expect lecture theatres with the combination of both natural wall and table top materials to have the highest average thermal comfort votes. It was those with heavily processed walls and natural table tops that had the highest average, however.

It is also worth noting that rejecting the null hypothesis does not necessarily prove that there is a causal relationship between thermal comfort and the above factors. Multiple confounding factors may have contributed to the observations above. It could be that the lecture theatres with cool coloured walls and table tops, and heavily processed walls and natural table tops may have lighting fixtures of lower colour temperatures or 'warm' lighting compared to the others; or maybe the environmental controls of those lecture theatres are located in more visible locations which allowed the students to adjust the set point temperatures to their preferred levels etc.

Also, contrary to some studies (Fanger 1973; Rohles et al. 1976; Ohta et al. 2007), the statistical tests on the interior finish characteristics of texture and sheen did not show any statistical significant difference or any potential relationship with thermal comfort within the dataset used. The results, however, do not dismiss any potential relationship between those characteristics and thermal comfort even though they do not show up in the research dataset as once again, there may have been confounding factors.

5.1. Limitations of study and further research

It is worth noting that there may be confounding factors that may have affected the students' thermal sensation and satisfaction and ultimately the thermal comfort votes collected. These factors may be behavioural, physiological and psychological in nature (de Dear et al. 2013; Nicol & Humphreys 2002; Yao et al. 2009; Brager & de Dear 1998; de Dear, R.J. & Leow, K. & Foo, S. 1991).

First, the duration of the lectures differed. They generally lasted between 1 to 3 hours. This meant that students in the short 1-hour lectures may not have had time to acclimatise to the thermal conditions in the lecture theatre and may have responded differently to those whom were in another lecture theatre for a 3-hour lecture, even if the thermal conditions may have been similar. Some students may have changed their clothing level several times during the survey and this may have affected the results.

Second, although the dataset comprises of a good range of lecture theatres with varying interior finish characteristics and a large sample of student respondents, the data collection and surveys were conducted over multiple years with different external weather conditions.

Additionally, the survey did not collect information on factors such as the sociocultural background and acclimatisation levels of the students, which are shown to affect thermal comfort perceptions (Brager & de Dear 1998). It is possible that some of the lecture theatre survey sessions comprised of a larger proportion of international students with different expectations from their thermal environment, e.g. potentially acclimatised to higher indoor temperatures (Fanger & Toftum 2002) compared to their counterparts from temperate climates.

Furthermore, some students may have travelled out of the UK to a different climatic region before the questionnaire survey took place. They may have acclimatised to the local thermal conditions and this might have affected their thermal comfort levels and sensations during the survey (de Dear et al. 1997). Another significant confounding factor may be colour temperature of the lighting used in the lecture theatres, which was not covered in this study.

Despite the limitations outlined above, results from this study have indicated that an interesting relationship may potentially exist between thermal comfort perception and interior finish characteristics, such as degree of naturalness of materials and colour hue. In the UK, a large proportion of national energy use is attributed to maintaining indoor thermal comfort standards through thermal conditioning (Knapp 2015). Current practices are not in line with existing energy policies and regulations. Instead of following the conventional way of tackling thermal comfort issues through mechanical means to keep thermal conditions of buildings within a narrow band of acceptable conditions, the thermal comfort range could be larger, allowing occupants to adapt to their thermal environment (Brager & de Dear 1998; Vine 1986). Further studies on the topic may open up a wealth of possibilities in human thermal comfort understanding where comfort can be improved through evidence based and creative interior design solutions, such as using natural materials and colours, and with minimal or no mechanical means, thus improving people's sensory experiences of indoor spaces whilst reducing the carbon footprint of buildings.

6. Conclusions

This exploratory study set out to investigate the impact of interior finish characteristics on thermal comfort perception in learning spaces of higher education. A taxonomy of general interior finish characteristics was developed and was used to classify a large sample of lecture theatres across UCL into different groups for statistical analysis and hypothesis testing. From the statistical tests carried out on an existing dataset of thermal comfort surveys in these lecture theatres, it was found that there may exist a potentially interesting relationship between thermal comfort and the degree of naturalness and colour hue of the interior finishes of UCL lecture theatres. Further analysis also found that a relationship may exist between various combinations of wall and table top finish characteristics and thermal comfort. The findings above were in line with previous studies that have acknowledged the psychological effects that interior finish characteristics may have on occupant thermal comfort perception.

Being a mental state, thermal comfort perception is a subjective entity which is influenced by tangible physiological and behavioural elements, as well as intangible psychological elements, such as past experiences and current expectations. Similar to how architects and designers have often made use of intangible aspects of the environment such as form and materiality to create different experiences, this study focused on how intangible aspects of the environment may have a part to play in human thermal comfort perception. The findings of this study may potentially help to inform future explorations into the interesting relationship between thermal comfort and the materiality of spaces. From here, there are endless opportunities for further research focusing on interior finish materiality and thermal comfort. Future research should test the effects of specific interior finish characteristics under similar experimental conditions such as temperature, RH, clothing level, experiment duration etc. They should also take into account external weather and preferably be conducted in applied settings with a good mix of subjects from different sociocultural backgrounds. The interior finish characteristics should be varied an element at a time in order to dissociate their individual effects on thermal comfort. Such studies may be of practical interest to suppliers and manufacturers of construction materials as well as architects and designers for whom reducing building energy consumption as well as the health and wellbeing of occupants are increasingly becoming a priority. Also, academics and governments alike may be interested in the actual energy savings potential of addressing thermal comfort issues through interior space materiality rather than conventional mechanical means.

References

Alexander et al. 1977. *A pattern language : towns, buildings, construction*. New York : Oxford University Press.

ASHRAE. 2013. ANSI/ASHRAE Standard 55 - Thermal Environmental Conditions for Human Occupancy. Atlanta, ASHRAE Inc. pp. 3-6.

Augustin, S. 2009. *Place advantage : applied psychology for interior architecture.* Hoboken, N.J. : Wiley.

Auliciems, A. 1981. *Towards a psycho-physiological model of thermal perception.*
International Journal of Biometeorology, 25(2), pp.109-122.

Bennet, C.A. 1972. *What's so hot about red.* Human Factors,14, pp.149–154.

Berry, P.C. 1961. *Effect of colored illumination upon perceived temperature*. Journal of Applied Psychology, 45, pp.248–250.

Brager et al. 2004. *Operable windows, personal control and occupant comfort.* ASHRAE Transactions, 110 (2), pp. 17–35.

Brager, G. S. & de Dear, R. J. 1998. *Thermal adaptation in the built environment: a literature review.* Energy and Buildings, 27, pp.83-96.

Chappells et al. 2005. *Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment*. Building Research & Information, 33(1), pp. 32-40.

Cohen et al. 1986. *Behavior, health, and environmental stress*. New York ; London : Plenum Press.

de Dear et al. 1997. *"Developing an Adaptive Model of Thermal Comfort and Preference." Final Report – ASHRAE RP-884*. Sydney: American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. and Macquarie Research, Ltd.

de Dear et al. 1998. *Developing an adaptive model of thermal comfort and preference.* ASHRAE Transactions,104, pp.145-167.

de Dear et al. 2013. *Progress in thermal comfort research over the last twenty years*.
Indoor air,23(6), pp.442-61.

de Dear, R.J. & Leow, K. & Foo, S. 1991. ***Thermal comfort*** in the humid ***tropics***: Field experiments in ***air conditioned*** and naturally ventilated ***buildings*** in Singapore.
International Journal of Biometeorology, 34(4), pp.259-265.

Eliasson et al. 2007. *Climate and behaviour in a Nordic city.* Landscape and Urban Planning, 82(1), pp.72-84.

EN ISO 7730. 2005. *Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria (ISO 7730:2005).* British Standards Institute.

Fanger et al. 1977. *Can colour and noise influence Man's thermal comfort?* Ergonomics, 20, pp.11-18.

Fanger, P.O. 1970. *Thermal comfort: analysis and applications in environmental engineering*. New York: McGraw-Hill.

Fanger, P.O. 1973. *Assessment of Man's Thermal Comfort in Practice.*
British Journal of Industrial Medicine, 30(4), pp.313-324.

Fanger, P.O & Toftum, J. 2002. *Extension of the PMV model to non-air- conditioned building in warm climates.* Energy and Buildings, 34(6), pp. 533-536.

Fountain, M. & Brager, G. & de Dear, R. 1996. ***Expectations** of **indoor climate control.***
Energy & Buildings, Vol.24(3), pp.179-182.

Gregory, R.L. 1970. *The intelligent eye*. London: Weidenfeld & Nicolson.

Healey et al. 2012. *Exploring the influence of qualitative factors on the thermal comfort of office occupants.* Architectural Science Review, 55(3), p.169-175.

Heijs et al. 1998. *Research on residential thermal comfort: some contributions from environmental psychology*. Journal of Environmental Psychology, 8(3), pp. 235-247.

Hirashima et al. 2016. *Daytime thermal comfort in urban spaces: A field study in Brazil.* Building and Environment,107, pp.245-253.

Holl et al. 2006. Questions of perception: phenomenology of architecture. New Ed.

San Francisco : William Stout.

Huebner et al. 2016. *Saving energy with light? Experimental studies assessing the impact of colour temperature on thermal comfort.* Energy Research & Social Science, 15, pp.45-57.

Humphreys et al. 2016. *Adaptive thermal comfort : foundations and analysis.* London ; New York : Routledge, Taylor & Francis Group.

Knapp, K. 2015. *A study of modifications to the geometry of an interior envelope and the effect on mean radiant temperature and occupant thermal comfort.*

Rensselaer Polytechnic Institute Troy, New York : ProQuest LLC.

Kobayashi et al. 1992. *Physiological responses to illuminance and color temperature of lighting*. The Annals of Physiological Anthropology, 11(1), pp.45–49.

Mangone et al. 2014. *Constructing thermal comfort: Investigating the effect of vegetation on indoor thermal comfort through a four season thermal comfort quasi-experiment.* Building and Environment. 81, pp.410-426.

Microsoft Corp. 2017. Load the Analysis ToolPak. [online] Retrieved from https://support.office.com/en-gb/article/Load-the-Analysis-ToolPak-6a63e598-cd6d-42e3-9317-6b40ba1a66b4?ui=en-US&rs=en-GB&ad=GB.

Mors et al. 2011. *Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts*. Building and Environment, 46(12), pp. 2454-2461.

Nicol, J.F. & Humphreys M.A. 2002. *Adaptive thermal comfort and sustainable thermal standards for buildings.* Energy & Buildings, 34(6), pp.563-572.

Nikolopoulou et al. 1999. *Thermal comfort in urban spaces: Different forms of adaptation*. REBUILD International Conference: The Cities of Tomorrow, Barcelona, 4-6 October 1999.

Nikolopoulou et al. 2001. *Thermal comfort in outdoor urban spaces: Understanding the human parameter.* Solar Energy, 70(3), pp. 227-235.

Nikolopoulou, M. & Steemers, K. 2003. Thermal comfort and psychological adaptation as a guide for designing urban spaces. **Energy & Buildings, 35(1), pp.95-101.**

Ohta, H. et al. 2007. *Effects of redecoration of a hospital isolation room with natural materials on stress levels of denizens in cold season.* International Journal of Biometeorology, 52(5), pp.331-340.

Pallasmaa, J. 2005. ***The eyes of the skin*** : architecture and ***the*** senses.

Chichester : John Wiley.

Parsons, K. C. 2003. *Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort and performance.* 2ND Ed, London : Taylor & Francis.

Poppelreuter, T. 2012. *Sensation of Space and Modern Architecture: a psychology of architecture by Franz Löwitsch*. The Journal of Architecture, 17(2), pp.251-272.

Qin et al. 2014. *The effect of indoor plants on human comfort.* Indoor and Built Environment. 23(5), pp.709-723.

Rajapaksha, I. 2017. *Effect of spatial ambience on thermal adaptation in tropics: Case of free-running shared spaces in coastal hotels of Sri Lanka.* Procedia Engineering,180, pp.975-985.

Roessler, K. K. 2012. *Healthy Architecture! Can environments evoke emotional responses?* Global journal of health science, 4(4), pp. 83-89.

Rohles, et al. 1976. *INTERIOR DESIGN, COMFORT AND THERMAL SENSITIVITY*. Journal of Interior Design, 2(2), pp.36-44.

Rohles, F. 2007. *Temperature & Temperment: A Psychologist Looks at Comfort.* ASHRAE Journal, 49(2), pp.14-16,18,20,22.

Ritterfeld, U & Cupchik, G.C. 1996. *Perceptions of interior spaces*.

Journal of Environmental Psychology,16(4), pp.349-360.

Vine, E. L. 1986. *Saving Energy the Easy Way - an Analysis Of Thermostat Management*. Energy, 11(8), pp.811-820.

Willey, H.B. 1987. *Proceedings of the European Conference, Newcastle upon Tyne, UK, 15–17 September 1987.* pp. 305–316.

Wohlwill, J. 1974. *Human adaptation to levels of environmental stimulation.*

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Personal control over indoor climate in office buildings in a Mediterranean climate - Amman, Jordan

Farah Al-Atrash[1], Runa T. Hellwig[2], Andreas Wagner[1]

[1] Karlsruhe Institute of Technology, Building Science Group, Karlsruhe, Germany. Email: farahatrash@gmail.com

[2] Augsburg University of Applied Sciences, Energy Efficiency Design, Building Physics and Indoor Climate, Augsburg, Germany.

Abstract: The objective of this study is to increase understanding of personal control in office workplaces by: 1) analysing the adaptive opportunities available to the occupants, how they perceive these adaptive opportunities, as well as their desire to have these opportunities. Statistical analyses were conducted to find out the impact of available control on perceived control, and interrelations between perceived availability and desired control; 2) mapping of how often these controls were used (exercised control); 3) analysing the reasons for not exercising available adaptive opportunities; 4) analysing the effect of office types and seasons on perceived control; and 5) determining the impact of perceived control on thermal comfort perception and air quality. For this, data from longitudinal surveys which have been conducted during four seasons in three office buildings in the Mediterranean climate of Amman, Jordan were analysed. Operable windows and adjustable thermostats are the most desired adaptive opportunities. The most stated reason for not exercising available adaptive opportunities was ‘No need to change’. The study found significant correlations between office types and perceived control. On the other hand, no significant correlation was found between seasons and perceived control. Perceived control correlates positively with occupants’ thermal comfort perception.

Keywords: Perceived control, adaptive opportunity, occupant behaviour, thermal comfort, air quality, mixed mode

1. Introduction

Personal control has a considerable impact on individual perception and satisfaction with the indoor climate; however, little is known about which aspects (e.g. available adaptive opportunities, reasons for not exercising adaptive opportunities, office type, season, occupants’ expectations as well as the psychological issue of both the belief of having access to the adaptive opportunities and the effectiveness of having this access) are important to determine personal control (Gossauer & Wagner 2006, Boerstra et al., 2013, Hellwig 2015).

Paciuk (1990) distinguishes three levels of personal control: available, exercised, and perceived control. Available control is evident in the access to adaptive opportunities like operable windows, adjustable thermostats, adjusting clothing, etc. Exercised control is how often a building’s occupant is engaged in adaptive behaviours in order to reach comfort. Recent work defines perceived control by the extent to which occupants believe they can cause desired changes of the indoor climate. Besides the objective availability of controls, their perceived availability and a person’s expectation towards control, perceived control also depends on the experiences of the occupants with their indoor environment and their personality as well as social and cultural expectations (Hellwig, 2015).

This paper investigates the impact of available control, perceived availability and desired control or rather the consistency of perception of adaptive opportunities and the conformity to expectation (desire) with perception of control. Furthermore, the effect of perceived control on thermal comfort and air quality perception is investigated. The paper aims to contribute towards a better understanding of personal control in office workplaces in different season and office type.

2. Methods

Data were collected in three office buildings during four seasons (spring, summer, autumn 2016 and winter 2017). These buildings are located in Amman which has a hot-summer Mediterranean climate (Csa) according to Köppen-Geiger climate classification (Rubel et al., 2017). Two of these buildings, building 1 and building 2, are mixed mode buildings and were awarded LEED GOLD certificate. The third building represents a naturally ventilated and passively cooled traditional building. Both mixed mode buildings are mechanically ventilated buildings with decentralized HVAC systems as the temperature can be adjusted by the occupants in each office. The built-up areas are 25,600 m^2, 28,218 m^2 and < 500 m^2 for buildings 1,2 and 3 respectively.

Figure 1. Building 1, building 2 and building 3 respectively.

In total, a sample of 119 occupants was willing to participate in the longitudinal survey. The number of occupants differs slightly between the different seasons. During summer, 74 persons took part in the survey, followed by spring, winter and autumn with 67, 62 and 57 participants respectively. Table 1 shows the distribution of participants among the three buildings.

Table 1. Number of participants in the three buildings per season.

building	season			
	spring	summer	autumn	winter
building 1	37	39	31	28
building 2	23	29	21	28
building 3	7	6	5	6
total	67	74	57	62

The data were gathered according to the following procedure: Firstly, the researcher objectively assessed available control opportunities in the offices. Exercised control was documented while occupants were completing the set of questions. Secondly, building occupants completed a set of questions about available, perceived and desired control, as well as exercised control and the reasons why not having exercised the available adaptive controls, thermal comfort perception and air quality perception. Table 2 shows the set of questions related to this paper. The questions were available in both Arabic and English languages.

The occupants answered the set of questions twice a week for a period of two to three weeks per season. The mode of responses for each person per each question has been calculated for each season for the nominal scales, while the median was calculated for ordinal scales.

Spearman's rank correlation (2-tailed, α=0.05) was used to analyse correlations between variables on the ordinal scale level. Spearman's rank correlation coefficient ranges between -1 and +1), in which -1 indicates a perfect negative correlation while +1 indicates a perfect positive correlation. We used Kruskal-Wallis test (α=0.05) to identify the differences of the median of perceived control in dependence on more than two different independent groups.

Table 2. Questions related to this paper.

Question	Response categories
Perceived availability Do you have these options in order to control the indoor climate? Operable window, door to interior space, door to exterior space, blinds, personal fan, personal heater and thermostat.	- yes - no
Desired control Do you prefer having the opportunity to adjust these options in order to control the indoor climate? (at the moment)? Operable window, door to interior space, door to exterior space, blinds, personal fan, personal heater and thermostat.	- yes - no
Exercised control What type of adjustment did you make to the given 'options to control indoor climate' during the last hours? Operable window, door to interior space, door to exterior space, blinds, personal fan, personal heater and thermostat.	- opened without asking others - opened after asking others - closed without asking others - closed after asking others - no adjustment - not applicable
Reasons for not exercising available controls What were the reasons you did not take the given 'options to control indoor climate'?[1)] Operable window, door to interior space, door to exterior space, blinds, personal fan, personal heater and thermostat.	- Would not have helped - Cannot adjust option any further - Was not agreeable to others in the space - Not sure if it would be OK with management - Not worth asking others' permission - Not worth disturb my work - No need-co-worker did this - Wanted to exhaust other control options first - I was comfortable enough
Perceived control How much control do you have to change 'the thermal conditions' of your office (at the moment)?	no control at all (1)… a lot of control (5) five-point ordinal scale
Thermal comfort perception How do you rate the temperature at this moment in your office?	very uncomfortable (1)… very comfortable (5). five-point ordinal scale

Air quality perception	
How do you perceive the air quality at this moment in your office?	very bad (1)… very good (5) five-point ordinal scale

1) Categories after Langevin (2014)

3. Results

3.1. Objective availability

The analysis of objectively available controls has been related to the office type. Only offices occupied by participants in the survey were considered. Both, building 1 and building 2 are mechanically ventilated buildings and contain three office types as follows: single offices, shared offices inhabited by two to five persons in building 2 and two to three persons in the case of building 1. The third type is an open plan office shared by up to ten persons. The third building is a relatively small free running office building which has single offices and one open plan office shared by around six persons. Figure 2 shows the distribution of office types within the three buildings.

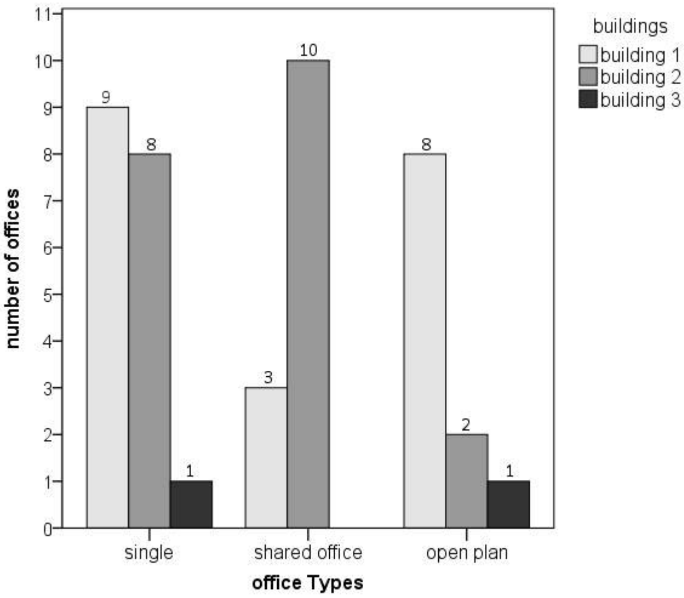


Figure 2. Prevalence of office types within the three buildings.

Figure 3 shows the available controls in offices of building 1. Building 1 has nine single offices. All offices have operable windows, interior doors, blinds and adjustable thermostats. Just one of them has an exterior door to access a terrace. The only available controls in shared offices are interior doors and adjustable thermostats. These offices were occupied by six persons. Occupants in these offices rely on mechanical ventilation to provide fresh air. In all open plan offices, adjustable thermostats are available, while two offices lack the availability of operable windows and blinds. One office doesn't have an interior door. The exterior door to a terrace was available in one office. The open plan offices were occupied by 46 persons.

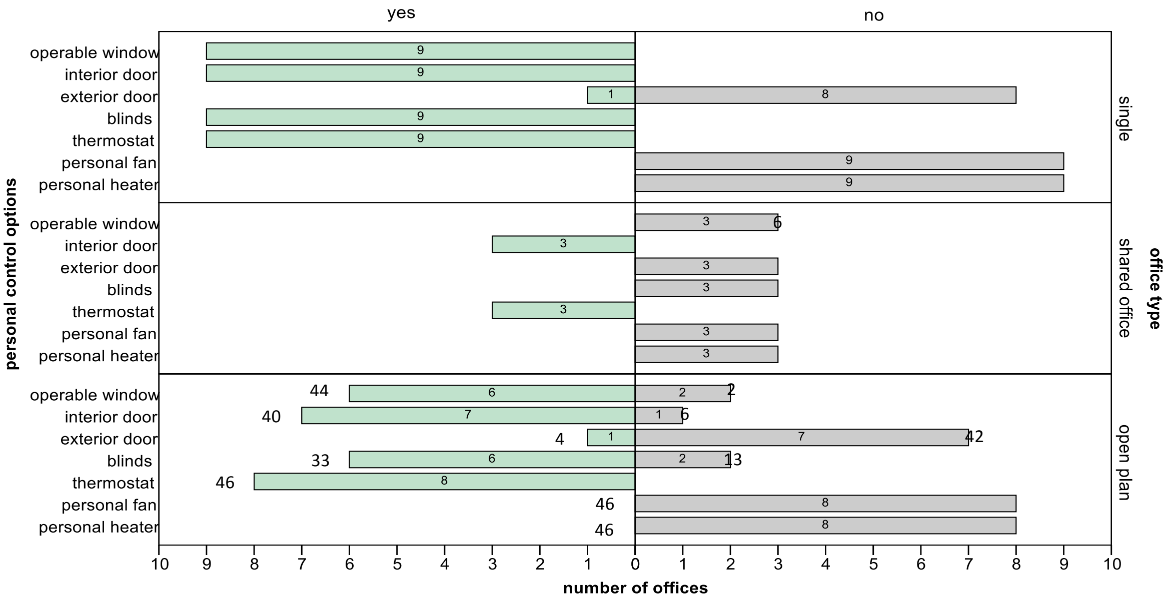


Figure 3. Available controls in offices of building 1. Numbers outside the boxes refer to the number of persons.

Figure 4 shows the available controls in offices of building 2. Building 2 has eight single offices. All of them have interior doors and adjustable thermostats. One office lacks operable windows, two offices do not have blinds. None of the single offices has access to a terrace. Personal fans and heaters were not found in any of the offices. The single offices were occupied by nine different persons (instead of eight) because the occupancy of one office changed during the longitudinal survey. All shared offices have interior doors and thermostats. Three offices lack operable windows as well as blinds. Two offices have access to a terrace. A personal fan was found in one of these offices. Personal heaters were not available. There were 32 people in these offices. Open plan offices have operable windows, interior and exterior doors in addition to thermostats. They lack blinds, personal fans and heaters. Open plan offices were shared between nine persons.

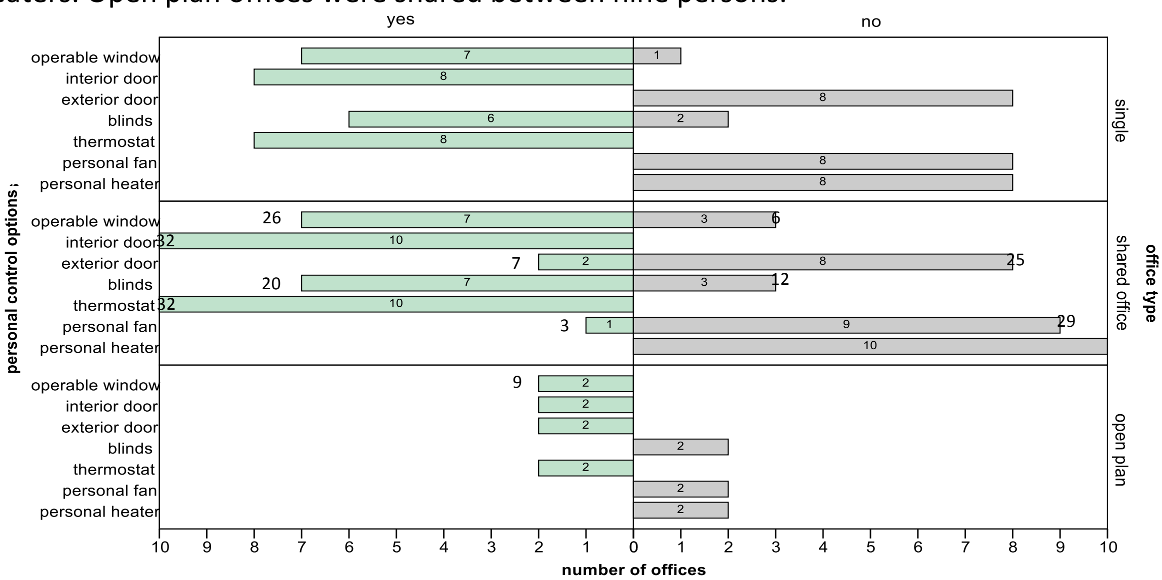


Figure 4. Available controls in offices of building 2. Numbers outside the boxes refer to the number of persons.

Figure 5 shows the available controls in offices of the third building. The single office in building 3 has operable windows, an exterior door, blinds, a personal fan and a personal heater. The open plan office which was shared by six persons has operable windows, interior door, blinds and personal heaters.

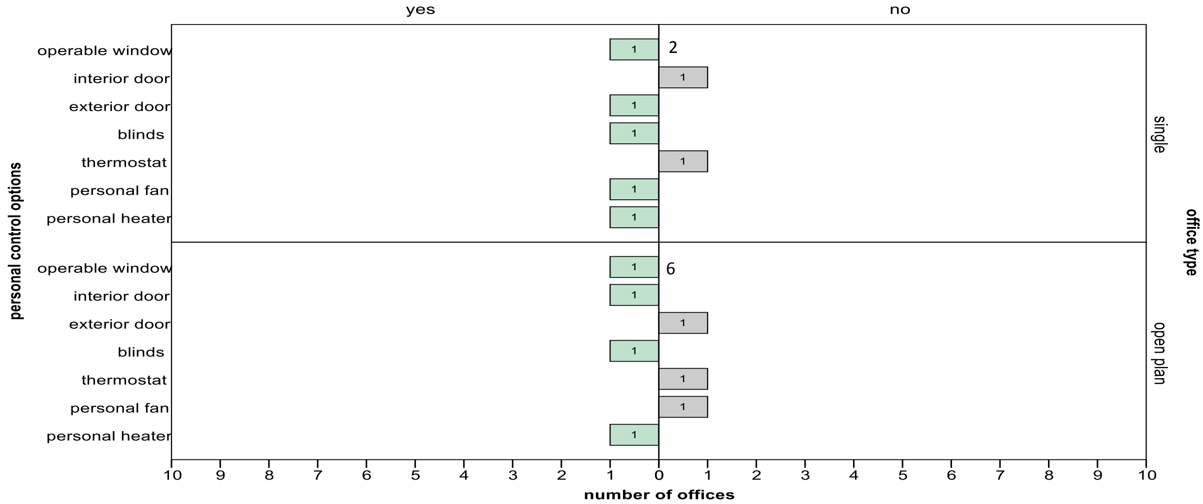


Figure 5. Available controls in offices of building 3. Numbers outside the boxes refer to the number of persons.

3.2. Perceived availability

Perceived availability in this study is defined as the subjective perception of availability of certain controls. It relates to the subjective opinion or belief of having or not having adaptive control options available.

Figure 6 shows the perceived availability of controls in building 1. All nine occupants of the single offices believe that they have access to operable windows, interior doors, blinds and adjustable thermostats. Three occupants reported perceived availability to control exterior doors. All six occupants of the shared offices stated having the availability to control interior doors and adjustable thermostats. Two of them declared the absence of operable windows and blinds. One occupant believed he/she was able to control exterior doors. The occupants of the open plan offices reported differing perceptions on the access operable windows, interior doors, blinds and adjustable thermostats. Twelve persons out of 46 stated perceived availability of exterior doors. In none of the offices, did occupants believe that they have control over personal fans and heaters.

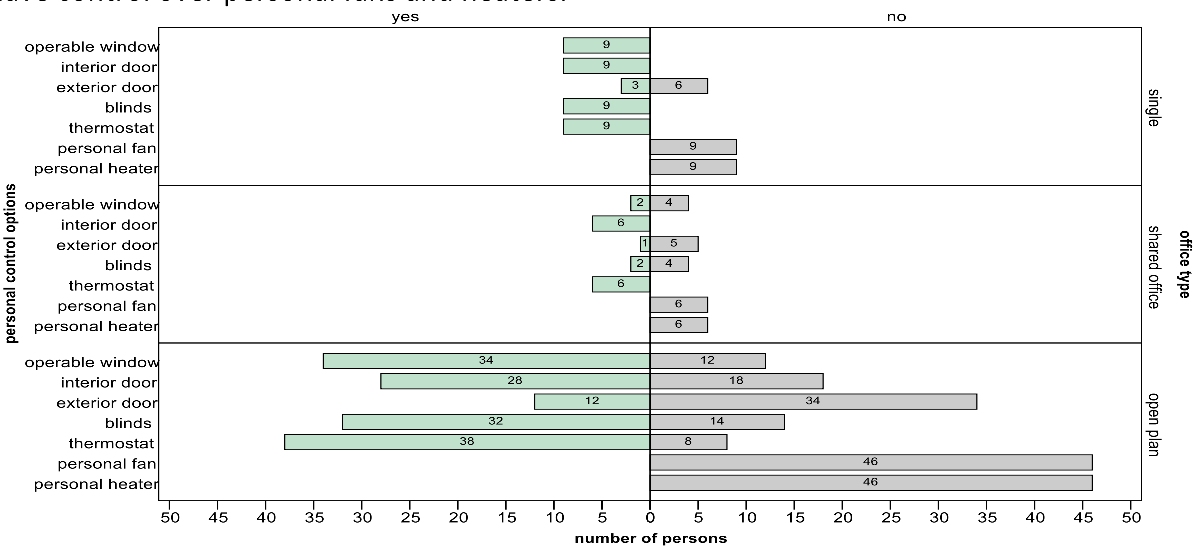


Figure 6. Occupants' perceived availability of controls in building 1.

Figure 7 shows the perceived availability of each person in building 2. Almost all occupants in all three office types reported having control over windows and interior doors.

Occupants in open plan offices perceived availability to control exterior doors. However, approximately half of the occupants of other office types did. Five persons in single offices stated having control over blinds, compared to only two in open plan offices. However, only five occupants declared not having control over blinds in shared offices. Thermostats were perceived to be available by all except for one in the shared offices. Concerning personal fans and heaters, no occupants of the single and open plan offices stated having this control option. In the shared office, less than 5% reported having these options.

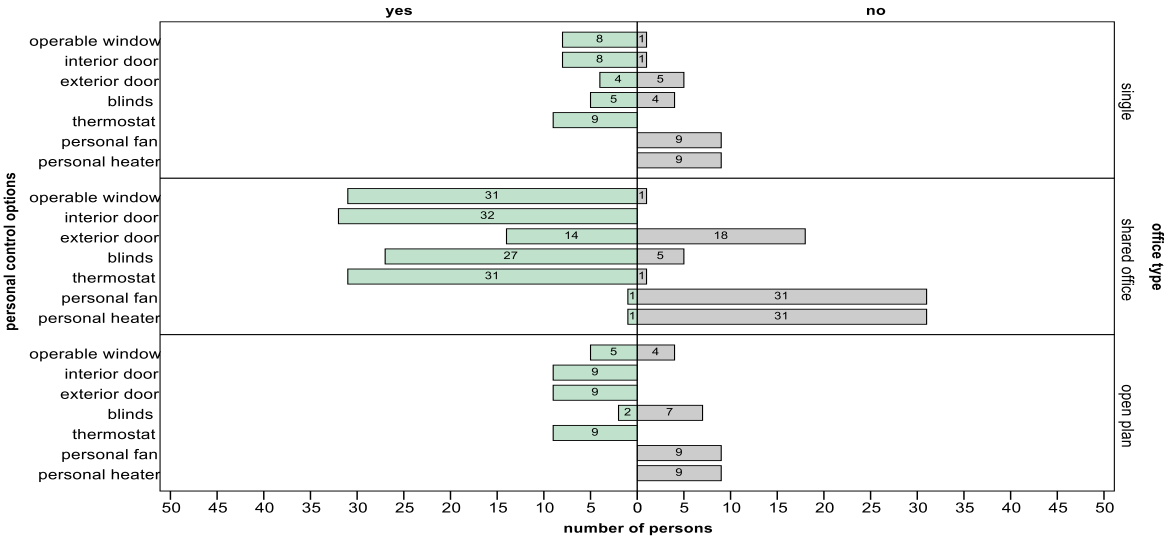


Figure 7. Occupants' perceived availability of controls in building 2.

Figure 8 shows the perceived availability of each person in building 3. All occupants in single and open plan offices stated they have control over operable windows and blinds. Six occupants of the open plan offices stated having control over the interior doors, while the two in the single offices did not. This can be explained by the fact that the single office only had access to an exterior door. None of the occupants in the open plan office perceived availability to control exterior doors. Only one person in both, single and open plan offices, stated having control over a personal heater. Concerning the personal fan control option, one person in the single office answered yes, but no one had such control in the open plan office.

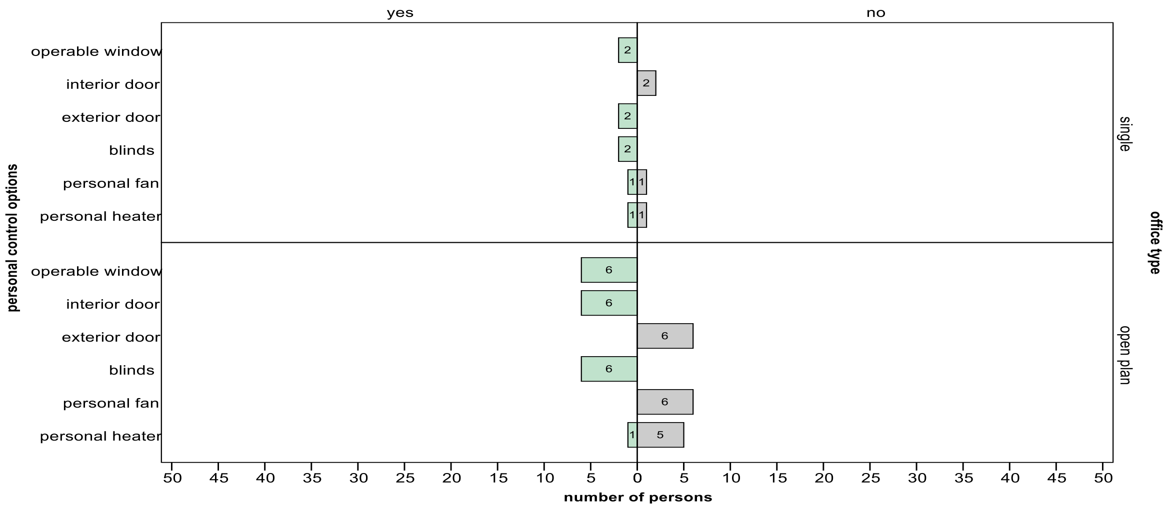


Figure 8. Occupants' perceived availability of controls in building 3.

3.3. Desired controls

This study defines desired controls as the wish for control options to adjust the indoor climate. The referred question to this part is: Do you prefer having the opportunity to adjust these options in order to control the indoor climate?

Figure 9 shows the desired controls responses of building 1. None of the occupants in shared offices wished to have control over personal fans and heaters, while some of the single and open plan occupants did. Operable windows and adjustable thermostat were the most desired control options in all office types.

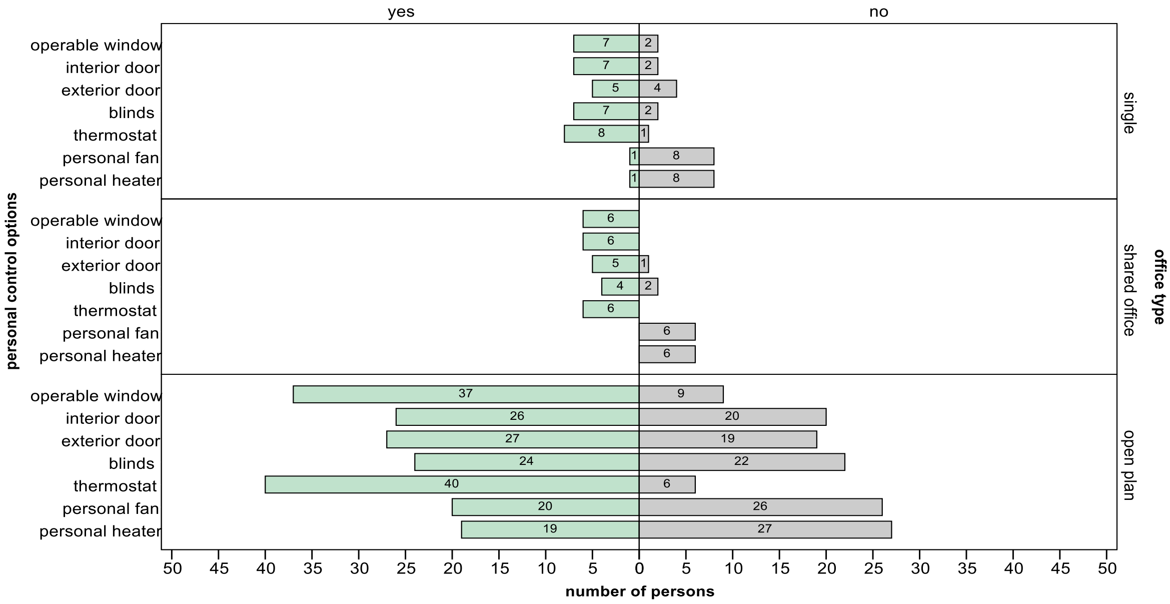


Figure 9. Occupants' desired controls in building 1.

Figure 10 shows the controls desired in building 2. Most of the occupants in both single and shared offices wished to have control over operable windows, interior doors, blinds and adjustable thermostats. Some of them wished to have control over personal fans and heaters. Interior doors and thermostats were the most desired control options in the open plan offices. The wish to have personal fans and heaters also appeared in this office type.

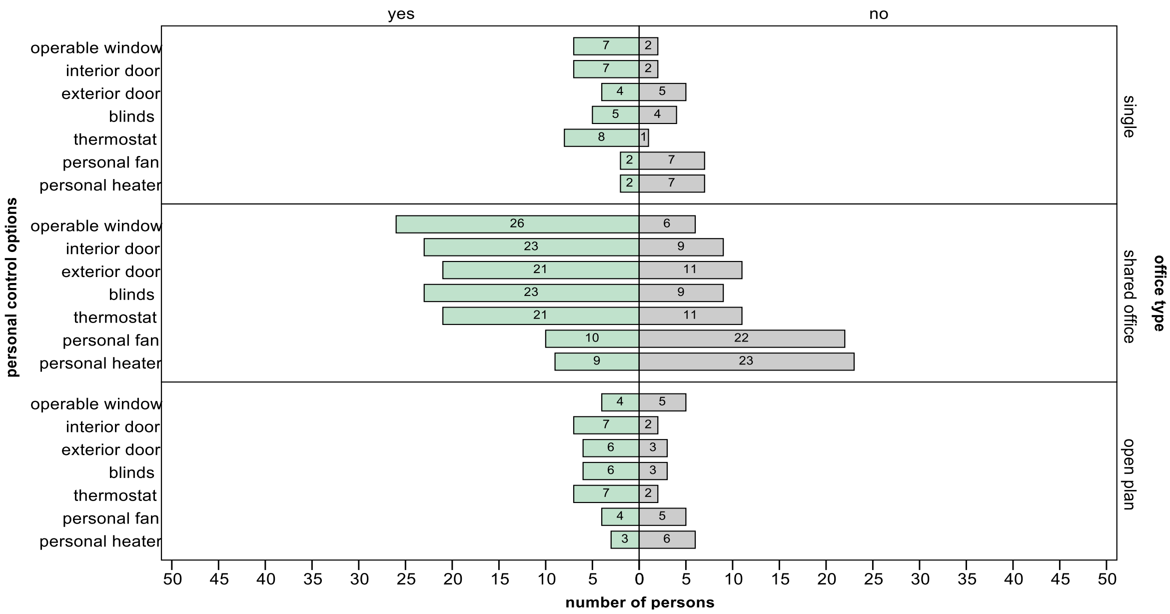


Figure 10. Occupants' desired controls in building 2.

Figure 11 shows the occupants' desired controls in building 3. In the single office, the most desired control options were interior door, exterior door, blinds, adjustable thermostat, personal fans and personal heaters, followed by operable window and interior door. While the most desired control option at the open plan office was adjustable thermostat.

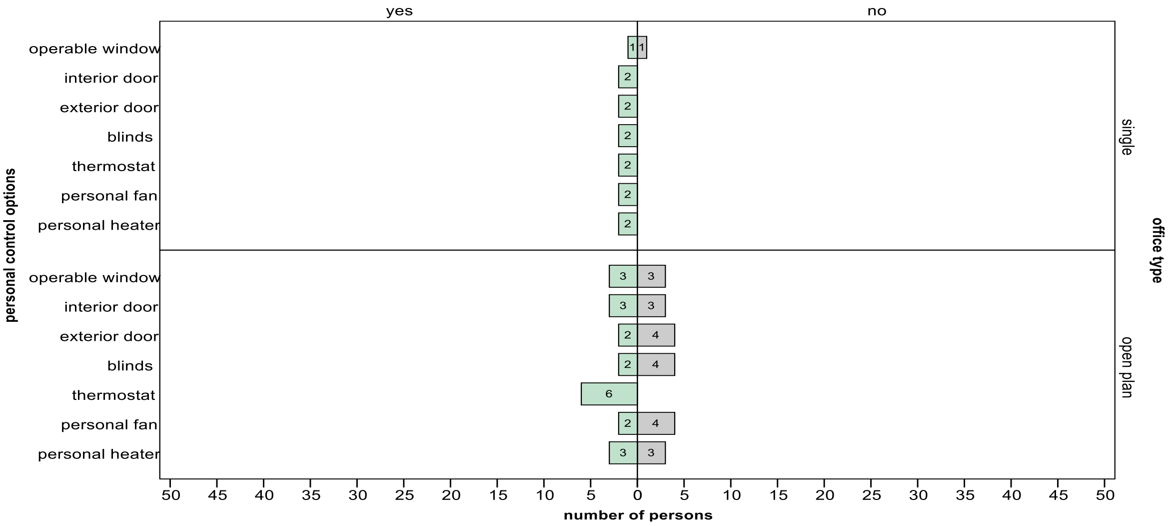


Figure 11. Occupants' desired controls in building 3.

3.4. Consistency of perceived availability and objective availability

In order to compare the perceived availability with the objective availability, in other words to provide proof of consistency between perception and reality, objective availability was subtracted from perceived availability. The answers of the related questions are binary, whereby +1 stands for 'having the control option' and '0' for 'not having the control option'. A difference of '0' means that the occupants' perception was consistent with the real conditions. An outcome of '-1', means the occupants may perceive some restrictions accessing the respective control option. A difference of '+1' indicates that they assume having this control option available although it is not objectively available in their working environment (Table 3). In this case the occupants even never tried to change the thermal environment with this control option or this control option is not important from their point of view.

Table 3. Categories of consistency between perceived availability and objective availability.

perceived availability	0	0	1	1
objective availability	1	0	1	0
difference	-1	0		+1
category	restriction	consistency		false positive assumption

Figure 12 shows the prevalence of categories of consistency between perceived availability and objective availability in the three buildings. In the case of the single offices, two persons believed they had access to outdoor space in building 1, while four persons did in building 2. The perceived availability of the other control options was consistent with the objective availability in building 1. One person believed to have access to blinds in building 2. There was the perception of restricted access to interior doors and blinds in building 2.

The perceived availability of controls in shared offices in building 1 was consistent with the objective availability for adjustable thermostats and interior doors, but not for operable windows and blinds which two persons believed to have access to, as well as for an exterior door which one person believed to have access to. In building 2, perceived availability was in accordance with the objective availability only for interior doors. There was the perception of restricted access to exterior doors, blinds and thermostat.

In building 1, perception of restrictions appeared in open plan office type for all control options with the smallest share for access to exterior doors and the largest share for interior doors. In the case of building 2, restrictions were perceived in the open plan office type just in the case of operable windows. In building 3, the perceived availability of most of the control options was in accordance with the objective availability. Restrictions were perceived for personal fans and personal heaters in the single office and for personal heaters in the open plan office.

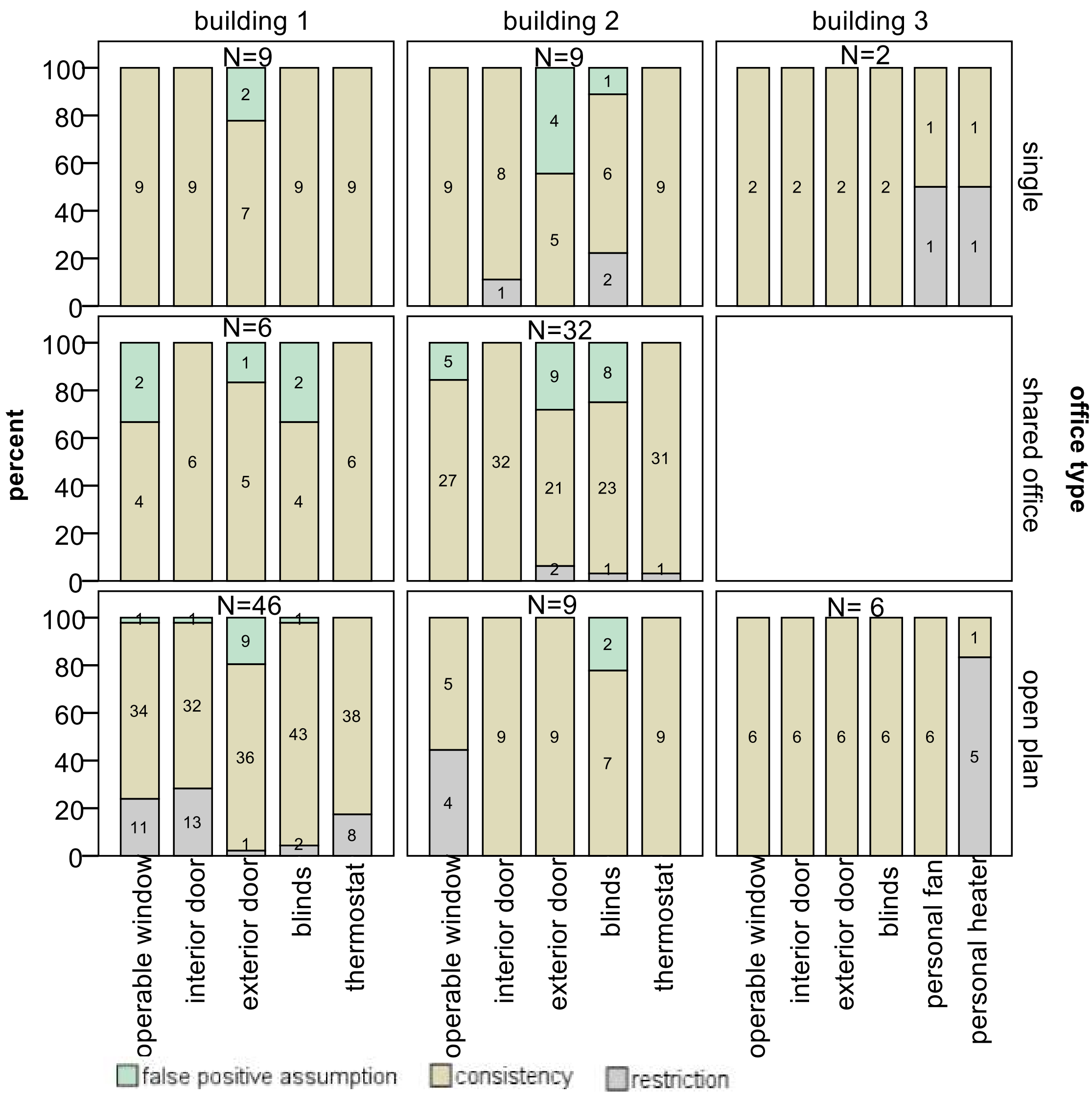


Figure 12. Categories of consistency between perceived availability and objective availability in the three buildings. Numbers in the columns represent the absolute number of occupants.

For each category of consistency between perceived availability and objective availability (Table 3) the distribution of the occupants' votes on perceived control was displayed (Figure 13) and analysed. The analysis shows no significant differences of the three categories' median of perceived control (p= 0.2). Median perceived control scores for the categories 'consistency' and 'false positive assumption' lie at 4 while the median score for the category 'restriction' is 3.

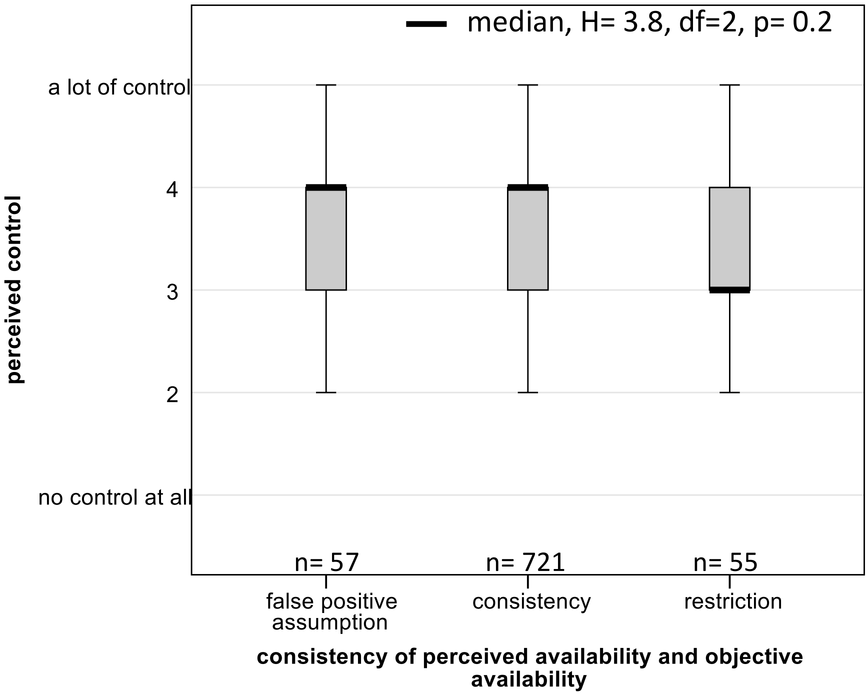


Figure 13. Perceived control for the three categories of consistency between perceived and objective availability.

3.5. Conformity between perceived availability and desired controls

The same principle as in section 3.4 was applied when investigating the level of conformity between perceived availability and desired controls. Desired controls responses were subtracted from perceived availability replies. A result of '0' means, the office control options match exactly the occupant's expectation. An outcome of '-1' can be interpreted as a perception of a lack of control, hence a negative non-conformity to expectation. A value of '+1' means that more control options are perceived to be available than the occupant desired, leading to a positive non-conformity to expectation (Table 4).

Table 4. Categories of conformity between perceived availability and desired controls.

<table>
<tr><td>perceived availability</td><td>0</td><td>0</td><td>1</td><td>1</td></tr>
<tr><td>desired controls</td><td>1</td><td>0</td><td>1</td><td>0</td></tr>
<tr><td>difference</td><td>-1</td><td colspan="2">0</td><td>1</td></tr>
<tr><td>category</td><td>negative non-conformity</td><td colspan="2">conformity</td><td>positive non-conformity</td></tr>
</table>

Figure 14 shows the frequency of the categories of conformity between perceived availability and desired controls in the three buildings. Building 1: In the case of single offices, the perceived availability of operable windows, interior doors, blinds and adjustable thermostats is in conformity with desired controls or shows positive non-conformity. Four persons desired exterior doors but did not perceive their availability. Some occupants in shared offices lacked the opportunity to control operable windows, exterior doors and blinds while few occupants in open-plan offices missed the opportunity to control operable windows, interior and exterior doors blinds, and thermostats. Building 2: In single offices, the results were similar to those in building 1, but the category negative non-conformity appeared also for operable windows and blinds. Occupants in shared offices lack the opportunity to control operable windows, exterior doors and blinds, while in open plan offices, occupants only missed the operable windows and blinds control options. Occupants in building 3 lacked the opportunity to control interior doors in the case of the single office and the exterior door in the open plan office, as well as personal fans and personal heaters in both offices.

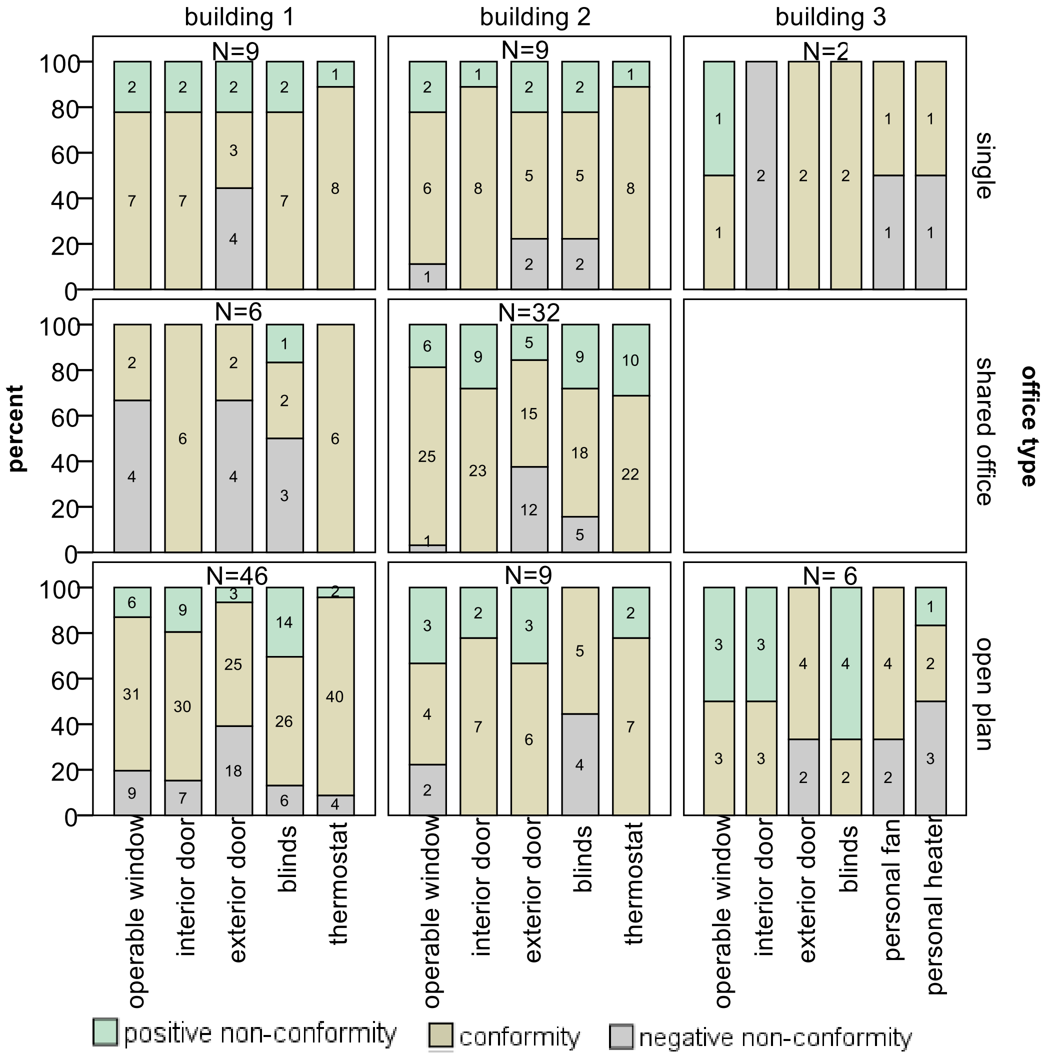


Figure 14. Categories of conformity between perceived availability and desired controls in the three buildings. Numbers in the columns represent the absolute number of occupants.

For each category of conformity between perceived availability and desired controls (Table 4) the distribution of the occupants' votes on perceived control was displayed (Figure 15) and analysed.

The analysis shows significant differences of the three categories' median of perceived control (p= 0.00). Median perceived control scores for the categories 'conformity' and 'positive non-conformity lies at 4 while the median score for the category 'negative non-conformity' is 3.

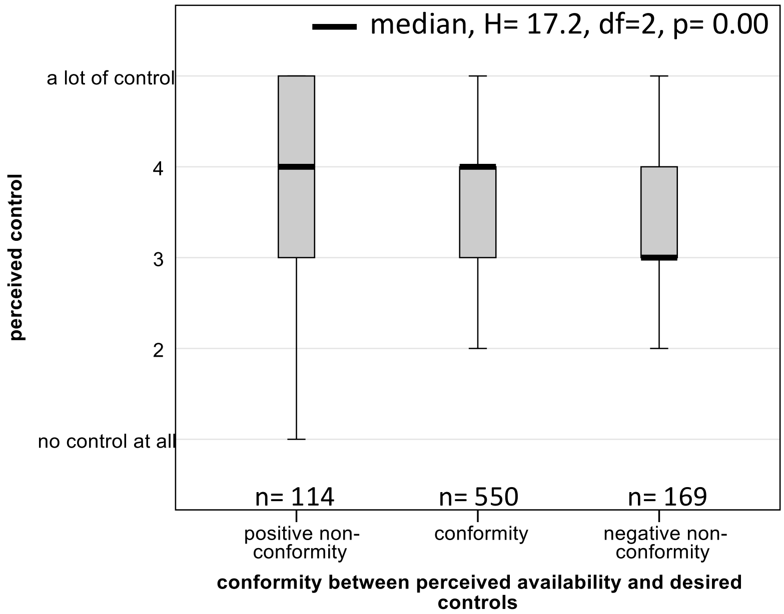


Figure 15. Frequencies of perceived control votes for the three categories of conformity between perceived availability and desired controls.

3.6. Exercised control

Exercised control was investigated as a function of the office type in all four seasons. Exercised control was calculated by percentage and with reference to the number of occupants who perceived available control. Figure 16 displays the result for exercised control in spring. In single offices, the frequencies of responses are distributed equally between 'opened without asking others' and 'no adjustment' (44%). In both, the shared offices and the open plan offices the highest prevalence is in 'no adjustment' (62%). The other responses are distributed evenly between the other control options. A similar trend as for spring was found among summer, autumn and winter: In single offices, the highest prevalence found was 'no adjustment', followed by 'opened without asking others' and 'closed without asking others'. In shared offices and open plan offices, 'no adjustment' shows the highest frequency. Followed either by opening the control options 'after asking others' or 'without asking others'. The lowest prevalence relates to closing the control options 'after asking others' or 'without asking others'.

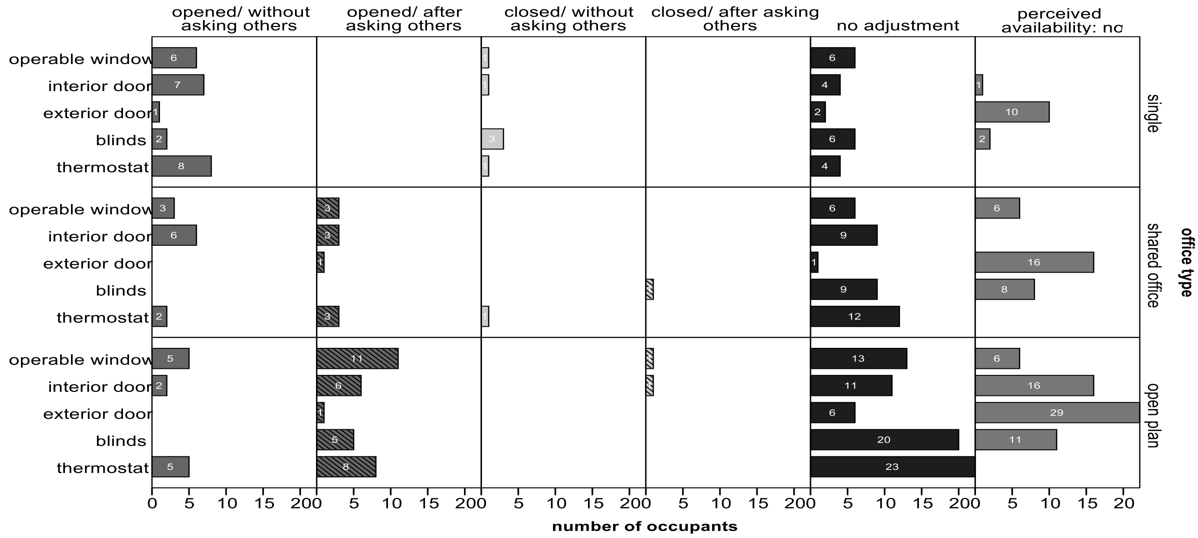


Figure 16. Exercised control in spring in all buildings.

3.7. Reasons for not exercising available adaptive controls

Results showed that the highest response rate to the question on exercised control was ‘no adjustment’ in all seasons. The reasons for not exercising available adaptive controls were divided into three main categories. The first one, ‘**no success expected**’ is applied when the occupants replied: ‘would not have helped’, ‘cannot adjust option any further’, ‘was not agreeable to others in the space’, and ‘not sure if it would be ok with management’. The second category is ‘**not important**’ with the following reasons: ‘not worth asking others’ permission’ and ‘not worth disturbing my work’. The third category is ‘**no need to change**’ with: ‘no need co-worker did this’, ‘wanted to exhaust other control options first’, and ‘I was comfortable enough’ as reasons given.

Figure 17 shows the reasons for not exercising available adaptive opportunities in spring. The most prevalent reason for not using indoor climate controls was: ‘I was comfortable’, with 56% in single offices, 44% and 47% in shared and open plan offices respectively. The third category ‘no need to change’ was the highest stated percentage category for not using indoor climate controls with 73%, 79% and 69% in single, shared and open plan offices respectively. The second category was related to ‘no success expected’ with 16%, 15%, 24% in single, shared and open plan offices respectively. The category ‘not important’ was the least reported one with 11%, 6% and 7% in single, shared and open plan offices respectively. The results of summer, autumn and winter seasons show a tendency similar to that found in spring’s results. The highest percentage for not exercising available adaptive opportunities was ‘I was comfortable’ for all office types among all seasons. Over all, the majority of responses fall in ‘no need to change’ category with the smallest percentage of 40% during winter in open plan offices. This percentage increased to 93% for single offices in summer. The second category ‘no success expected’ reflected the highest percentage of 54% in open offices in winter, while this percentage was 4% in single offices in autumn. Answers related to ‘not important’ were relatively few with a highest percentage of 14% in shared and open plan offices during autumn.

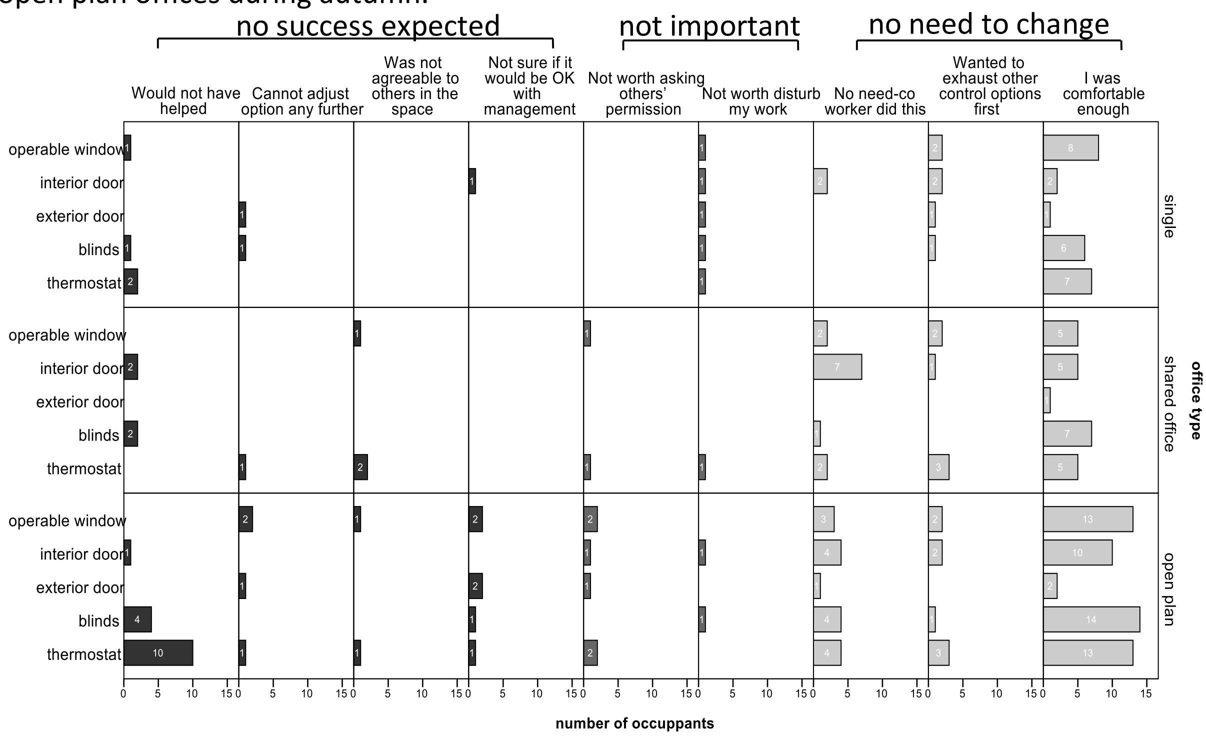


Figure 17. Reasons for not exercising available controls in spring.

3.8. Impact of office type and season on perceived control

A significant effect of the impact of office type on perceived control for each season is shown in Figure 18. Median value of perceived control for single office type is the highest in all seasons.

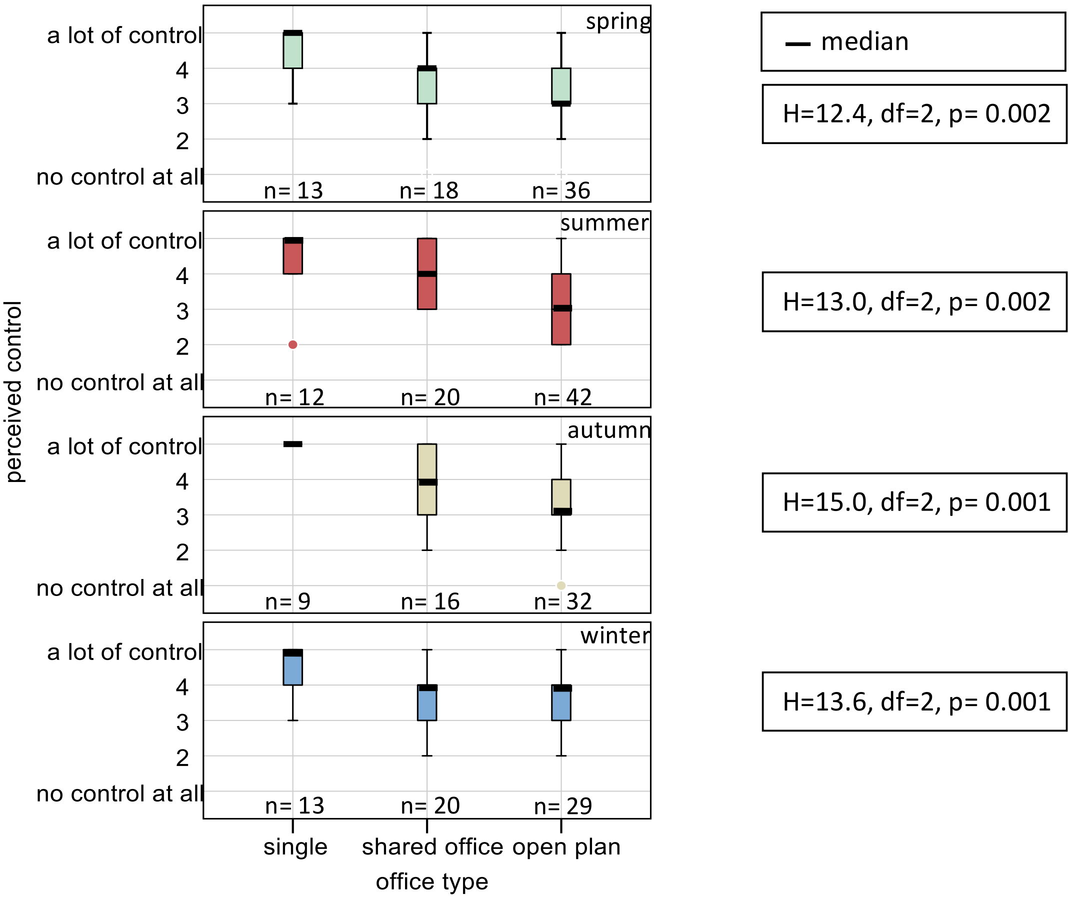


Figure 18. Perceived control versus office type in all seasons.

Concerning the impact of season on perceived control, overall scores for perceived control did not differ significantly (p=0.18) (Figure 19). The median of perceived control is 3 for spring and 4 for summer, autumn and winter.

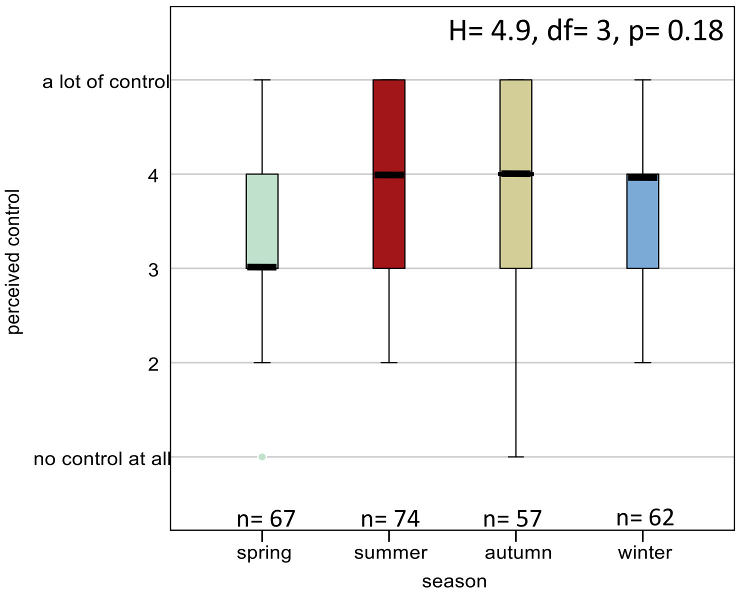


Figure 19. Perceived control versus season.

3.9. Impact of perceived control on thermal comfort and air quality perception

Concerning the thermal comfort perception, 92% of the occupants were neither comfortable nor uncomfortable to very comfortable (scale points 3 to 5) and only 8% voted for uncomfortable or very uncomfortable. Occupants also perceived a good air quality with 92% (scale points 3 to 5) and only 8% voted for bad or very bad air quality.

An analysis using Spearman rank-order correlation of perceived control versus thermal comfort perception and air quality perception respectively was carried out for all seasons (perceived control: no control at all (1)… a lot of control (5), thermal comfort: very uncomfortable (1)… very comfortable (5), air quality perception: very bad (1)… very good (5).

The strongest significant correlation was found for summer (rs =0.52; 2-tailed p= 0.00), followed by autumn, all seasons, winter and spring respectively as shown in table 5. This indicates that persons, who believe having control, are generally more thermally comfortable. Perceived control was also found to correlate positively with air quality perception among all seasons. The strongest correlation was found for all seasons (rs =0.51; 2-tailed p= 0.00) as shown in table 5. This suggests that persons, who believe having control, are more positive towards air quality.

Table 5. Spearman rank-order correlation between perceived control and both thermal comfort and air quality perception.

	perceived control versus thermal comfort perception		perceived control versus air quality perception		
	r_s	Sig. (2-tailed)	r_s	Sig. (2-tailed)	N
all seasons	**0.45****	**0.00**	**0.51****	**0.00**	119
spring	**0.34****	**0.005**	**0.32****	**0.009**	67
summer	**0.52****	**0.00**	**0.41****	**0.00**	74
autumn	**0.49****	**0.00**	**0.29***	**0.03**	57
winter	**0.42****	**0.00**	**0.41****	**0.00**	62

* correlation is significant at the 0.05 level (2-tailed)
** correlation is significant at the 0.01 level (2-tailed)

4. Discussion

In this study, a detailed longitudinal approach to analyse the impact of available control (objective and perceived) and desired controls on perceived control has been used. The mechanically ventilated buildings tended to provide bigger office units: in building 1 the majority (75%) of the participating occupants worked in open-plan office environment; in building 2 the majority (64%) worked in shared offices.

The most desired control options were operable windows (77% of the occupants) and thermostats (82%) in the three buildings. This proportion is somewhat lower but of similar magnitude as previous findings e.g. the ProKlimA - study showing that 85% of office workers wish to have control over their indoor environment (Bischof et al. 2003). The most desired control features should be provided to the occupants as these are the features the occupants are likely to use, and this will lead to a positive perception of self-efficacy (Hellwig, 2015). The less desired control options in the mechanically ventilated buildings were personal fans and heaters, while these options were desired by occupants in the free running building 'building 3'.

As shown in Figures 3, 4 and 5, single offices of the surveyed buildings offered more objectively available control options compared to shared and open plan offices. Non-operable windows were found in three shared offices in both building 1 and 2, and in two open-plan offices. This is surprising as both buildings are LEED certified, aiming also for high occupants' comfort and satisfaction. Although availability of control has not been an evaluation criterion in most green building evaluation systems, it is known for many years and from numerous SBS studies (e.g. Bischof et al. 2003) that sealed facades/non-operable windows contribute considerably to the prevalence of the sick building syndrome.

The occupants' perceived availability of all control options was lower in shared and open plan offices compared to single offices as shown in Figures 6, 7 and 8. Some occupants stated no availability of operable windows and blinds in open plan offices in both mechanically ventilated buildings, although these opportunities were available. Furthermore, restrictions accessing the available control options obviously appeared in shared and open plan offices (Figure 12). This is related to the nature of these office types as many persons with different personalities and needs had to work close to each other. Some occupants were sitting relatively far away from the mentioned control options and stated not having exercised them for the reasons: 'would not have helped', 'cannot adjust option any further', 'was not agreeable to others in the space', and 'not sure if it would be OK with management'. Thus, they perceived restrictions from making adjustments. This is in line with Leaman and Bordass (1999) who found that when negotiations with others are needed before exercising the control options, constraints may appear.

New variables have been introduced: consistency of perceived and objective availability and conformity to expectation. Overall, the vast majority of votes (n=721) showed consistency of objective and perceived availability of control. This means that the majority was aware of the adaptive opportunities available at their workplace.

Only 55 votes expressed perceived restrictions with regard to controls. Although the Kruskal-Wallis-test for the median difference of perceived control of the categories of consistency between perceived and objective availability was not significant, votes expressing perceived restrictions in accessing controls led to a one scale point lower level of perceived control compared to all other votes (n=778, Figure 13). Restrictions may result from the objective availability of control options in the buildings or the social environment -here work- (management, negotiations, norms), leading to a lower level of perceived control in the workspace (Hellwig, 2015).

Conformity to expectation was also introduced in this study as it is seen as part of a person's evaluation system for judging the indoor environment (Hellwig, 2015). An expectation which is not met by the indoor climate or the building can also have an impact on perceived control or comfort perception. The majority of votes (n=550) demonstrated conformity to expectation. This means that the expectation of the majority towards control was met. 169 votes expressed a negative non-conformity to expectation; hence expectation was not met. The Kruskal-Wallis-test for the median difference of perceived control of conformity between perceived availability and desired controls was significant, votes expressing negative non-conformity led to a one scale point lower level of perceived control compared to all other votes (n=664) (Figure 15). A higher degree of conformity to expectation was shown to be prevalent in naturally ventilated office types compared to mechanically ventilated buildings. If offices lack some control options, occupants in these offices desired having these missed control options. Those who missed some control options scored at a lower level on the perceived control scale.

The results related to exercised control opportunities were similar among the four seasons. The highest percentage of exercised control opportunities was 'no adjustment' in all buildings among the four seasons as occupants felt comfortable. Even if 'no adjustments' were made most of the time, it would not justify reducing the availability of control opportunities, as availability is an important positive feature as such in a workspace.

Furthermore, the correlation between perceived control and both, thermal comfort and air quality perception, has been investigated. Perceived control has shown a positive significant correlation with thermal comfort and air quality perception during all seasons (Table 5). This was also shown by Boerstra (2016) who showed that perceived control acts as a mediator of the relation between indoor climate and comfort perception.

We found no significant differences in perceived control level with regard to season; although the median of perceived control in spring was 1 scale point lower compared to the other seasons. In contrast, Gossauer, Leonhart & Wagner (2006) found that the effectiveness of temperature changes was lower in summer compared to winter affecting the satisfaction with the thermal conditions in summer negatively.

Votes on perceived control showed significant differences between office types among the four seasons, as perceived control in single offices was the highest among all seasons. This was reflected on a higher level of perceived control, thermal comfort and air quality perception in single offices.

5. Conclusion

This study investigated the impact of available control on perceived control, interrelations between perceived availability and desired control, as well as the effect of perceived control on thermal comfort and air quality perception. It also analysed the exercised control that took place in offices and the reasons behind not adjusting the available control options. Another main objective of this study was to investigate whether different seasons and office types affect perceived control.

Our analysis showed that larger office units offered less control -not only objectively- but also according to occupant's perceived availability of certain controls and according to perceived control votes. Also, this study confirms that operable windows (and thermostats) are a highly desired feature of workspaces and therefore buildings should preferably be designed with operable windows if external environmental conditions are suitable for that. Windows and thermostats were also the most adjusted control options during all seasons. But the most prevalent control exercise was 'no adjustment' because the most stated reason for not exercising available controls in all buildings and among the different seasons was a positive thermal comfort perception.

Negative non-conformity between perceived and objective availability of controls could have an impact on perceived control but was not significant in our study, maybe due to the low number of votes in this category. Perceived control could be shown to be affected significantly by conformity to expectation.

Furthermore, perceived control correlates positively with both thermal comfort and air quality perception during all seasons and also in each season separately. So, improving the availability of adaptive opportunities in buildings can positively affect occupants' comfort perception.

This study contributes to a better understanding of what affects personal control and how perceived control is linked to thermal comfort and air quality. It also shows the role of office types and seasons on perceived control. Further analysis is needed to understand the effect of different seasons on perceived control.

Acknowledgement

The authors would like to give their appreciation to both the employers and the employees of the World Health Organization (WHO), Middle East Insurance Company (MEI), and Yaghmour Architects for participating in the survey presented in this paper and for facilitating conducting the survey in their buildings.

6. References

Bischof, W., Bullinger-Naber, M., Kruppa, B., Schwab, R., & Mueller, B. H. (2003). Expositionen und gesundheitliche Beeintraechtigungen in Buerogebaeuden – Ergebnisse des ProKlimA-Projektes. Stuttgart: Fraunhofer IRB

Boerstra, A., Beuker, T., Loomans, M., & Hensen, J. (2013). Impact of available and perceived control on comfort and health in European offices. Architectural Science Review, 56:1, pp 30–41.

Boerstra A.C., (2016). Personal control over indoor climate in offices: impact on comfort, health and productivity. PhD thesis. Eindhoven: Eindhoven University of Technology. Available via: http://repository.tue.nl/850541.

Gossauer, E., Wagner, A., (2006). Post Occupancy Evaluation and Thermal Comfort - State-of-the-Art and new Approaches. Annual Journal of Advanced Building Energy Research, Vol. 1, December 2006

Gossauer, E.; Leonhart, R.; Wagner, A. (2006). Nutzerzufriedenheit am Arbeitsplatz. Eine Untersuchung in sechszehn Bürogebäuden. Gesundheitsingenieur, 127, 5, 232-240

Hellwig, R.T. (2005). Thermische Behaglichkeit. Unterschiede zwischen frei-und mechanischen belüfteten Büro-gebäuden aus Nutzersicht. PhD Thesis, Technische Universität, München.

Hellwig, R. T., (2015). Perceived control in indoor environments: a conceptual approach, Building Research & Information, 43:3, pp 302-315, DOI: 10.1080/09613218.2015.1004150

Paciuk, M., (1990). The role of personal control of the environment of thermal comfort and satisfaction at the workplace. Proceedings of the 1990 EDRA Annual Conference, pp 303-312

Langevin. J., (2014). Linking Environmental Adaptation, Personal Comfort, & Energy Use in the Built Environment, PhD Thesis, Drexel University, United States.

Leaman, A., & Bordass, B. (1999). Productivity in buildings: The ‘killer’ variables. Building Research and Information, 27:1, pp 4–19. doi:10.1080/096132199369615

Rubel, F., Brugger, K., Haslinger, K., Auer, I., (2017). The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800–2100

Using feature selection techniques to determine best feature subset in prediction of window behaviour

Hailun Xie[1], Shen Wei[2], Li Zhang[1], Bobo Ng[1], Song Pan[3]

[1] Faculty of Engineering and Environment, Northumbria University, Newcastle, UK, hailun.xie@northumbria.ac.uk;
[2] The Bartlett School of Construction and Project Management, University College London, London, UK, shen.wei@ucl.ac.uk;
[3] College of Architecture and Civil Engineering, Beijing University of Technology, Beijing, China, pansong@bjut.edu.cn;

Abstract: Previous studies have demonstrated diverse effects of different factors on occupant window behaviours. It is necessary to choose appropriate subsets of different behavioural window opening features, and to eliminate irrelevant and redundant features so as to avoid overfitting, noise and random fluctuations being learned by the model, and improve the accuracy of predictive models of window opening. The choice of protocols for the selection of features has been widely accepted as one of the most important steps in developing machine learning prediction algorithms. This study employed the use of both a recursive and a non-recursive feature selection method designed to consider all influencing factors simultaneously to explore the confounding effects inherent in various factors pertaining to the prediction of window opening behaviour. Two machine learning algorithms were applied as estimators in a recursive selection process, namely support vector classification (SVC), logistic regression (LR), and one in a non-recursive process, namely random forest (RF). Additionally, two processing schemes in the recursive method analysis were tried to determine the optimal feature subset based on corresponding algorithms, namely recursive feature elimination (RFE) and recursive feature elimination with cross validation (RFECV). Seven factors were considered in the feature selection process based on collected data, including: indoor temperature, outdoor temperature, relative humidity, concentrations of PM2.5, air quality index (AQI), wind speed and wind direction respectively. The results showed that different feature subsets can generate different prediction accuracy within the recursive method. RFECV can determine the most appropriate feature subset effectively with the consideration of the correlation among various factors. Both LR and SVC were proved to be effective as estimators embedded in RFECV, however SVC is more computationally expensive and LR shows a larger variance within the feature subset space. RF, as a non-recursive method, demonstrated real advantages in eliminating redundant features compared to the recursive feature selection process.

Keywords: Feature Selection; Recursive Feature Elimination; Cross Validation; Logistic Regression

1. Introduction

1.1. Study on window behaviour

Occupants in buildings can behave in a wide range of ways to maintain their comfort levels due to the many different adaptive opportunities they have to hand to adjust their thermal environment including the use of: thermostatic valves, HVAC system set points, window, blinds, shades operation, and plug loads. The 'dark side' of occupant behaviour in terms of building energy consumption can also result from inactivity and studies showed that in some commercial buildings 56% electricity was consumed during non-working hours due to leaving lights and equipment on at the end of day (Masoso and Grobler, 2010). Occupant behaviour can affect building energy consumption to an extent similar to that exerted by mechanical control, based on a study of experiment conducted in Switzerland (Filippín et al., 2005, Haas et al., 1998). Whether energy-saving strategies and technologies performs as expected has been found to largely depends on how occupants understand and interact while the building is in use (Yan et al., 2017). Therefore, to gain a better understanding the role played by occupant behaviour in the energy performance of a particular building is crucial for bridging gap between real and predicted energy performance.

The key intervention between perceived indoor environmental quality in buildings and the climate outdoors is the building envelop. Some parts of that envelope are immovable and some, the windows can open to allow the mixing of outdoor and indoor air. As a consequence, window operation is one of the most efficient strategies for producing a desired indoor micro-climate (D'Oca and Hong, 2014). Extensive studies focusing on various aspects of window opening behaviour have been conducted, including window behaviours under different heating or cooling mode, in different building types, and across different countries(Pan et al., 2018, Wei et al., 2013, Wei et al., 2014). According to previous studies, window behaviours can be influenced by a wide range of factors both “external” to occupant itself, (e.g. air temperature, air quality), and internal or “individual” (e.g. personal background, attitudes, preferences), and building properties (e.g. HVAC systems, ownership, building type). All drivers of window behaviour can be divided to five general categories: Physical (indoor and outdoor environment); Psychological (preferences, attitudes); Physiological (age, sex); Contextual (type of environment where the occupants are located); and social (income, lifestyle) (Fabi et al., 2012).

Statistical analysis has been extensively used to analyse associations and relationships among these various factors influencing building performance and occupant behaviour (D’Oca et al., 2014). Fritsch et al. developed a window opening angle predicting model related to outdoor temperatures in winter based on Markov chains in 1991 (Fritsch et al., 1990). Nicol was the first one using the method of probability distribution to predict window opening behaviour as logit functions of outdoor temperature (Nicol, 2001). Haldi and Robinson adopted three different methods, logistic regression, Markov chain, and random process, to make predictions on window behaviour respectively (Haldi and Robinson, 2009a). Based on previous extensive researches, drivers of window behaviour contain various factors both in numerical and categorical formats. In fact, different factors actually demonstrate different levels of importance in terms of the interrelationship with window behaviour. A predictive model with more variables doesn’t necessarily represent a model with better predicting performance. On the contrary, the inclusion of more factors in predictive modelling probably leads to the increase of model dimensionality, which would lead to a higher risk of overfitting problems, especially with limited sample sizes (De Silva and Leong, 2015). Therefore, it is very necessary to adopt a feature selection process to select of the more or most relevant factors and remove irrelevant, redundant, or noisy information in order to avoid the overfitting problem, noise and random fluctuations being learned in the model, in the process of predicting window behaviour.

1.2. Feature selection in window behaviour modelling

When it comes to the issue of the feature selection process in the prediction of window opening behaviour, it appears that strategies for choosing key features have been largely undiscussed in previous studies. Based on feature selection issues as raised in current studies three general categories stand out, which also reflect three problems of feature selection modelling of window behaviour.

Problem 1: The criterion and details for selecting a suitable feature subset in the prediction of window behaviours are not clear or thoroughly illustrated in some studies, which would make the selection results unsolid and increase the uncertainty about achieving an optimal prediction performance or being able to confidently compare results between parallel studies. One of the typical example is as follows: D'Oca and Hong (D'Oca and Hong, 2014) employed logistic regression to identify factors influencing window behaviour with monitored data from 16 private offices. Coefficients of all applied variables in logistic regression were calculated for each office. Somehow, they provided no further explanation about how to decide which feature was chosen based on these coefficients in logistic regression. However, several conclusions were made without specific description and analysis, for example, indoor air temperature, arrival time, occupant presence, time of day and outdoor temperature are some of the main factors influencing window opening behaviours. However, it still remains unclear and dubious about whether the results of selected feature subset in this study provide the optimal solution or not, because no criterion of selection was demonstrated in this study.

Problem 2: Feature selection processes in previous studies generally failed to take into account the collective effects of various factors on window behaviour simultaneously. Features in the prediction model were selected mainly by analysing and measuring the statistical correlations for every factor separately with window behaviour. By evaluating different factors separately, this correlation analysis cannot measure the confounding effects on window behaviour inflicted by the collective interaction of all factors.

In another typical example Herkel et al. (Herkel et al., 2008) carried out a study of window opening behaviour in 21 south-facing offices in Germany, in which seasonal effects, outdoor temperature, indoor temperature, time of the day and building occupancy were considered. Each factor was analysed and discussed separately to evaluate its significance to window behaviour. Then outdoor temperature and user occupancy depending on the time of the day were selected to construct a user model. Despite the elaboration in Herkel's study, it failed to take into account collective and confounding effects of various factors due to the separation of different variables, which made this study unable to determine the best feature subset capable of achieving the highest prediction accuracy.

Problem 3: Few studies on window behaviour modelling formulate a search strategy which can be effectively applied to deal with a large number of factors in the process of feature selection. For very limited number of studies which include feature selection processes before establishing their prediction model, each one only conducted several tests of intentional combinations of two or three factors, rather than proposing a complete and viable method to execute the possible feature combinations in the whole feature space. In 2009, Haldi and Robinson (Haldi and Robinson, 2009b) conducted a comprehensive study of interactions with window opening behaviours by office occupants based on seven years of continuous measurements and three modelling approaches. When dealing with feature selection, Haldi and Robinson adopted a 'wrapper method' using different attempts at including univariate, multivariate and polynomial logistic models to determine the better feature subset. Their feature selection process was wrapped inside the process of model training so that selected features can maintain its conformity to the calculation of the prediction algorithm to achieve a better performance. This is so far the most complete study on feature selection in prediction of window behaviour based on logistic regression. However, the researchers only made several trials of combining some factors with best relevance rather than provided a search strategy for feature combination in multivariate regression process, which makes this research unable to examine the confounding effects among factors attached with different importance levels. The criterion for determining the best model is dependent on parameters of goodness-of-fit, which can show a good performance in the model training stage, but it may not work effectively on a new dataset.

1.3. Aim of the study

In general, most feature selection processes in previous studies only considered each feature separately, thereby feature dependencies and redundancies could not be analysed, which may reduce their classification performance when compared to other types of feature selection techniques. Therefore, the study of window opening behaviour prediction currently lacks systematic feature selection techniques and protocols. In order to make the prediction models more accurate and lay a solid foundation for the application of far more complicated prediction algorithms in future, this study aims to make practitioners of window behaviour prediction aware of the necessity of feature selection and demonstrate both a recursive and non-recursive feature selection method, which can consider all influence factors simultaneously so as to take into account confounding effects among various factors. Two algorithms were used as estimators in recursive selection process, namely support vector machine (SVM), logistic regression (LR), and one in non-recursive process, namely random forest (RF). Cross validation and non-cross validation methods, recursive and non-recursive methods are discussed and compared based on the training results of the real-life data.

2. Research Methods

2.1. The data set

Data on window behaviour was collected based on an office building in Beijing University of Technology (BJUT). The field monitoring was conducted during two transitional seasons in 2014, from 16th March to 30th April, so that data of how occupants operate windows can be obtained without the interference of air conditioning systems. Five offices, each with two south-facing gliding windows as shown in Figure 1, on the first floor were chosen to monitor for occupancy (1min interval), window state (1min interval) and indoor temperature (T_i, 5min interval). Simultaneously, outdoor parameters, including outdoor temperature (T_o), PM2.5, air quality index (AQI), relative humidity (RH), wind direction (WD), and wind speed (WS), were also monitored by a weather station installed locally on the roof of case study building (Shen et al., 2015). All monitored factors are shown in Table 1 as followed.

Figure 1. The case study building and the outlook of monitored office

Table 1. Monitored factors in this study

	Monitored Factors
Outdoor Parameters	outdoor temperature, relative humidity, AQI, PM2.5, wind direction, wind speed
Indoor Parameters	Indoor temperature

2.2. Estimators in feature selection process

Many machine learning models can generate feature rankings inherently from their internal structures, or can be constructed for feature selection. This applies to regression models, random forest, SVM, etc. In this paper, different machine learning methods and processing approaches will be studied on the selection of relevant features to window behaviour.

(1) Logistic Regression (LR):

Logistic regression is a sigmoidal classification able to predict the probability of an event having binary outcome (0-1) occurrences, which has been extensively applied in prediction of window behaviour in previous studies. Logistic regression allows to express the magnitude of coefficients of each related variable as a function of the binary outcome.

$$Log\left(\frac{P}{1-P}\right) = a + b_1 \cdot X_1 + \cdots + b_n \cdot X_n + \cdots \quad (1)$$

where:

- P is the probability
- a is intercept
- b_{1-n} are coefficients
- x_{1-n} are variables

(2) Support Vector Classification (SVC):

Support vector machine can construct a hyperplane, which can be used to make classifications. In SVC, a hyperplane is selected to best separate the points in the input variable space by their classes, which is to maximize the margin between the two classes. SVC can not only solve the problem of linear classification, but also the problem of non-linear classification by applying for kernel function.

$$\min \frac{1}{2} ||w||^2 \;\; s.t. \;\; ,y_i(w^T x_i + b) \geq 1, i = 1, \cdots, n \quad (2)$$

where:

- w is the vector of the coefficients

(3) Random Forest (RF)

In many practical applications, it is almost impossible to generate a specific functional relationship between inputs and output. The decision tree method is conceptually simple, yet powerful nonlinear method that often provides excellent results (Tsanas and Xifara, 2012). Random forest applied in this study is an ensemble learning method by constructing a group of decision trees during training stage. The input features are successively split into different branches with smaller sub-regions so that similar response can end up in the same set. The tree stops growing until it is impossible to split anymore or a certain criterion has been met. Besides, tree models can be directly used for feature selection by the measure of impurity. Based on averaged impurity decrease values from each feature, features can be decided whether to be chosen or not. For classification, this measurement is typically called Gini impurity and information gain/ entropy, as followed.

$$H(T) = Entropy = -p * \log(p) - (1-p) * \log(1-p) \quad (3)$$

$$IG(T,a) = H(T) - H(T|a) \quad (4)$$

where:

- P is the percentage of positive samples
- a is corresponding attribute
- $H(T)$ is information entropy
- $IG(T,a)$ is information gain

2.3. Recursive feature elimination and cross validation

(1) Recursive Feature Elimination

Given the chosen estimator or classifier, different weights can be assigned to features, for example, the coefficients in generalized linear model. Recursive feature elimination (RFE) is based on the idea of selecting features by recursively considering smaller and smaller sets of features. Firstly, the estimator was trained on the initial set with all features, and importance of features can be obtained through training process by the attribute of estimator. Then, feature with least importance are pruned from current set of features. This procedure is recursively repeated until the desired number of features to select is eventually reached as shown in Figure 2. RFE is an effective method to get rid of some unimportant features preliminarily so as to reduce dimension of feature space when there are too many factors in training data.

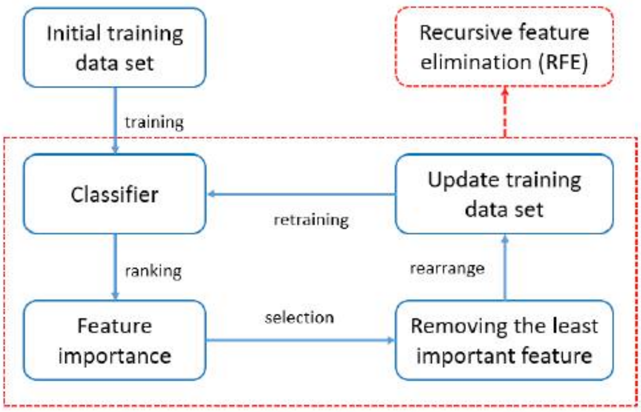


Figure 2. Diagram of recursive feature elimination (RFE)

(2) Cross Validation

When employing RFE, the number of remained features needs to be defined by practitioner rather than determined by some objective standards, which would bring in uncertainty of the final results. Cross validation can solve this problem by holding out part of data in training set as test data, then use trained model to predict on them. The best feature subset is the one with smallest error on the hold out test data. The prediction accuracy of test data in cross validation can provide criterion for RFE to determine the best feature subset. Therefore, recursive feature elimination with cross validation (RFECV) was applied to select features as shown in Figure 3.

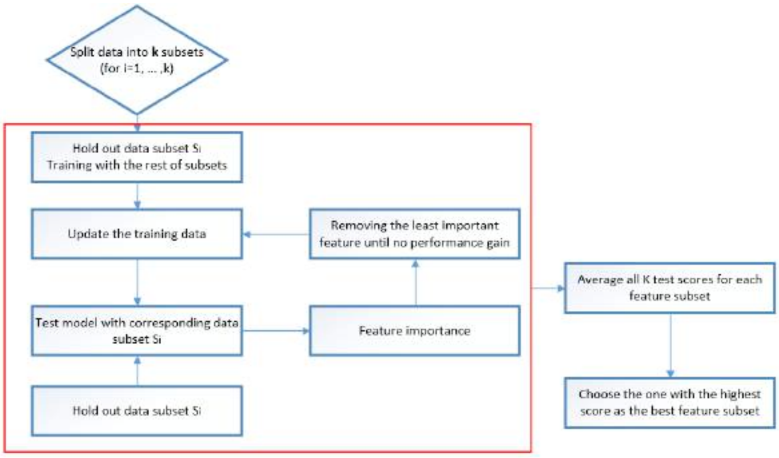


Figure 3. Diagram of recursive feature elimination with cross validation (RFECV)

3. Results and Discussion

3.1. Analysis of correlation among features

Perfectly corrected features are truly redundant in the sense that no additional information is gained by including all of them in the model. If highly correlated features are present, individual features would exhibit similar performance to the collective feature subset and computational price would accordingly increase (De Silva and Leong, 2015). Besides, including redundant features in predicting model may also mislead certain modelling algorithms and reduce prediction accuracy (Liu and Motoda, 1998). Therefore, eliminating redundant features before establishing predicting model is necessary in order to improve the model performance.

Figure 4. Correlation coefficients between different factors

The correlation coefficients among seven features have been calculated as shown in Figure 4. The highest correlation coefficient of 0.96 occurs between PM2.5 and AQI, which reasonable because PM2.5 is a sub-index in the evaluation of AQI. Besides, strong correlation can also be observed between indoor and outdoor temperature (0.58), relative humidity (RH) and PM2.5 (0.60), RH and AQI (0.55), wind speed (WS) and RH (-0.49). Such various correlations among all factors may change the prediction performance of each factor on window behaviour to some degree by imposing complex effects between each other. In order to eliminate the effects of redundant features and improve prediction accuracy, appropriate methods were applied by considering feature subsets rather than individual feature relevance assessment as followed.

3.2. Recursive feature elimination (RFE)

Recursive feature elimination has a great advantage in the elimination of unimportant features when the feature dimension of the model is relatively large. Although only seven features were considered which probably makes it not particularly necessary to apply RFE process, RFE was still employed in this study in order to provide insights in dealing with large feature dimension in window prediction and improve the universality of this study. Therefore, RFE with an estimator of logistic regression (LR) was applied to demonstrate a complete process for dealing with feature selection. Two of least important features among all seven are ruled out, which means five features are remained in process of RFE as shown in Table 2.

Table 2. The coefficients of remained features

Name of feature	T_i	T_o	PM2.5	RH	WS
Coefficient	0.3926	-0.1855	-0.0006	-0.0475	0.0127

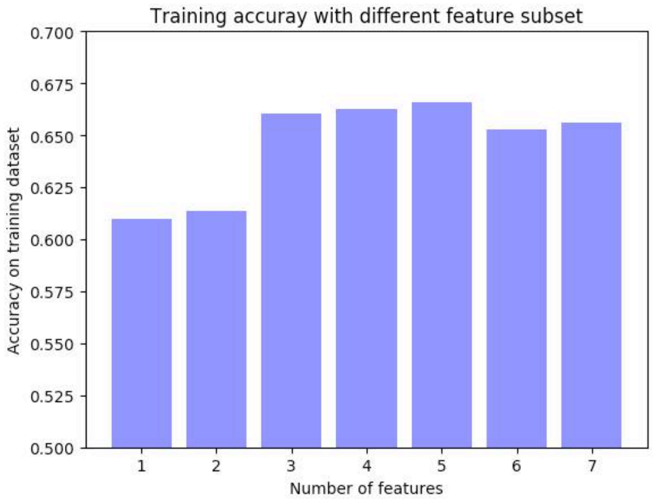


Figure 5. Training accuracy of RFE on different feature subset

Based on the results, AQI and wind direction are superseded among seven features, which means these two don't have a contribution as significant as other features to the prediction accuracy of window behaviour. Previous researches have pointed out that wind speed is not particularly correlated with window operation (Haldi and Robinson, 2009b), which is identical with the results in this study. As for AQI, it refers to the severity that air has been polluted, and is considered as an important and essential index for air quality. The reason that AQI is ruled out in RFE process is mainly because the data collection in this study was conducted during transitional seasons in Beijing, when central heating system in a city scale had been turn off during that period, so did all coal boilers used for central heating. Hence, the pollutants concentration in air was not as high as it was in winter, which can adequately explain why AQI is considered as an irrelevant feature by the RFE process. Additionally, the coefficient for PM2.5 is quite low compared with other coefficients in table 2, which indicates that PM2.5 has little correlation with window operation. The reason behind this low relevance of PM2.5 is quite similar as that of AQI, because PM2.5 is actually a sub-index in the evaluation of AQI in China.

When the raw data include too many features, it is very effective to apply RFE preliminarily removing part of irrelevant features. However, there is one drawback for RFE, which is the best feature subset cannot be decided by RFE process. Although the model accuracy based on training data can be calculated, there is no validation process to measure the predicting performance for various feature subsets combined based on training data. As shown in Figure 5, just because the subset with 5 features generates the best accuracy based on training data among all 7 feature subsets in RFE, it doesn't mean that this subset with 5 features would be exactly the best choice for the model because there is no prediction process on a new group of data to validate this idea. In order to obtain the best feature subset, the recursive feature elimination with cross validation (RFECV) can be applied based on the new feature dimension selected by RFE as a complimentary process.

3.3. Recursive feature elimination with cross validation (RFECV)

In the cross validation process, the whole training data will be divided into 10 folds, 9 of them used for training and one hold-out fold used for validation. The difference between RFECV and RFE is that in each feature subset the estimator will be examined in terms of making predictions on the data of hold-out fold in RFECV, hence the best feature subset can be determined by the rankings of CV scores, which is actually the prediction accuracy obtained by using number of correct predictions divided by the number of hold-out samples in cross validation.

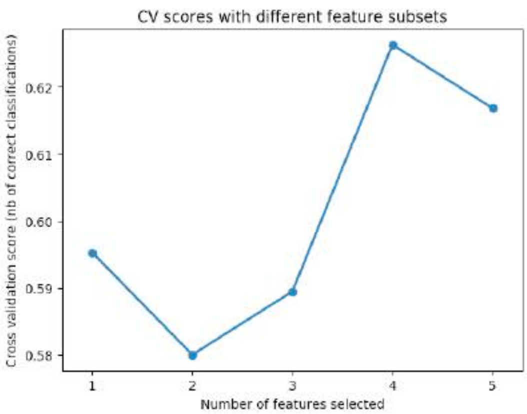


Figure 6. CV scores with remained five features

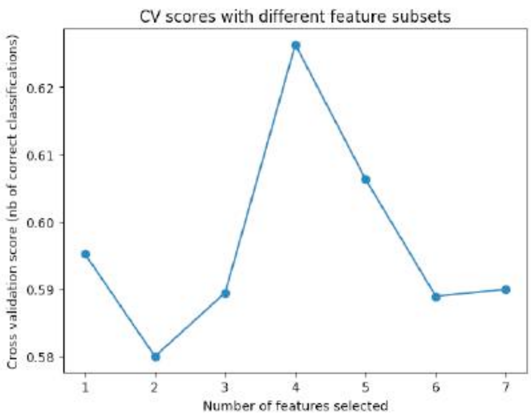


Figure 7. CV scores with original seven features

The RFECV has been applied firstly on the data set with remaining five features from the RFE process as shown in Figure 6. Based on the results, different feature subsets demonstrate different CV scores. The cross validation score reached up to a maximum of 0.626 when four features are retained in the model including T_i (indoor temperature), T_o (outdoor temperature), RH (relative humidity), and WS (wind speed), which means one more feature, PM2.5, can be further got rid of.

The strong relativity between indoor temperature, outdoor temperature, and window behaviour has been proved by many researches before (Parys et al., 2011), however RH and WS have been uniformly ignored because of their separate insignificant statistical correlation with window behaviour (Haldi and Robinson, 2009b). The problem is that the statistical significance analysis in previous researches was conducted without considering the confounding effects among features combinations on the prediction of window behaviour (Herkel et al., 2008, Shen et al., 2015), hence features with smaller relevance to window behaviour were ruled out at the first step. Based on the results in Figure 6, however T_i, T_o, combined together with RH and WS generates the best CV scores rather than merely temperature parameters, which in turn indicates that just because features don't have strong correlation with window behaviour, doesn't mean the combination of them cannot reach a better prediction accuracy. On the contrary, when features closely correlate with each other, they're likely to become redundant features which couldn't provide more useful information for the prediction in the model (Guyon and Elisseeff, 2003).

To validate the result, the original data set with all seven features were used again to apply RFECV as shown in Figure 7, the same result was obtained. Besides, the results also demonstrate that a model with more features doesn't necessarily lead to a better prediction accuracy, on the contrary, sometimes it would be totally counterproductive. When selected feature number is less than four, low CV scores indicate that the prediction model is likely to result in underfitting, which means the model cannot capture characteristics of the problem very well. Similarly, when more than four features are selected, the model is probably overfitting. Actually, when number of features is not very high in the model, RFECV can be directly used for determining the best subset of features rather than established on RFE. However, RFECV is more computationally expensive than RFE, in that case using RFE to deal with high dimensionality data firstly is very helpful. Therefore, according to results of RFECV the best feature subset on this training data includes four features, which are indoor temperature, outdoor temperature, relative humidity and wind speed respectively. It should be noted that this conclusion is only suitable in this dataset and estimator, rather than a universal conclusion.

3.4. Comparison between LR and SVC on results of RFECV

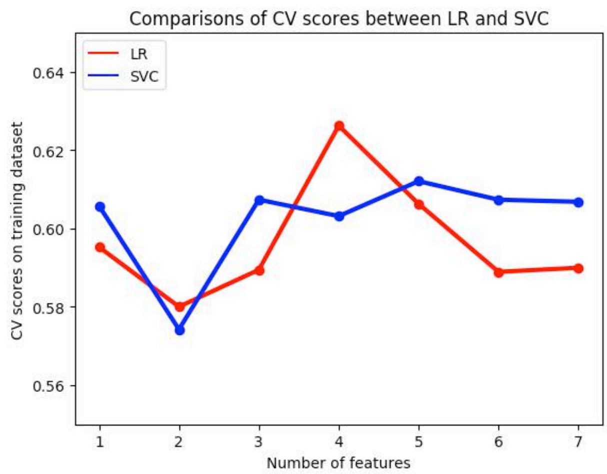


Figure 8. Comparison of CV scores between LR and SVC on various feature subset

The estimators mentioned above in RFE and RFECV are all based on logistic regression (LR). In this section, support vector classification (SVC) is applied for the estimator as a substitute of logistic regression. Based on Figure 8, CV scores for SVC in the whole range of feature subset demonstrate some variances to a degree, which has been previously proved in LR model that different feature subset can lead to different prediction accuracy. The highest CV score reaches up to 0.612 and occurs when five features are chosen, which are indoor temperature, outdoor temperature, PM2.5, relative humidity, and wind speed respectively.

Except for the subset with first two features, all other subsets display a relatively stable CV score, which is in the range of 0.60-0.62 with little fluctuations.

When compared with SVC, LR shows a larger variance through the whole range of feature numbers, and a higher maximum of 0.626 at the subset with four features. The general trend of the variety in CV scores is quite similar between SVC and LR, but prediction accuracy of SVC seems more robust on different the feature number compared to LR. However, this stability needs to be investigated further by testing on new dataset. Generally, the results show the validity of both methods in feature selection based on similar CV scores of both, however, the better one of them can only be determined by using new data to make predictions and comparing the accuracy of predicting results among these two methods in terms of bias and variance.

3.5. Random forest on feature selection

Unlike RFE or RFECV, tree models perform feature selection process by the measure of impurity embedded inside the algorithm rather than by iterations, which makes tree models much more computationally efficient than RFE methods. In this study, random forest (RF) has been employed as a non-recursive method to complete feature selection process and constructed by 10 decision trees. For classification, feature importance can be evaluated by the reduction of Gini impurity.

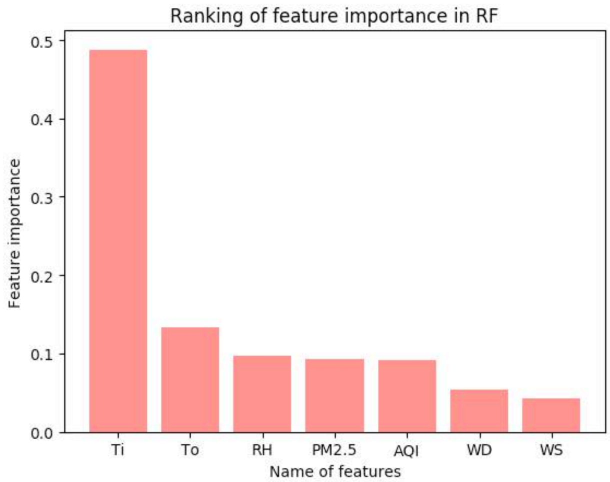


Figure 9. Feature rankings based on RF

As shown in Figure 9, indoor temperature is most important among all seven features and has a great advance in terms of the normalized values of feature importance. Then outdoor temperature comes second, followed by relative humidity, PM2.5 and AQI with little variance in feature importance. The similar importance level among relative humidity, PM2.5 and AQI based on tree model conforms the results of high correlation among these three features in 3.1. However, it should be noted that when there are highly correlated features present in the tree model, any of these correlated features can be chosen as predictor with no preference one over others. Once one of them is determined, the importance of others would be significantly reduced since the reduction of impurity have been mainly executed by the first chosen feature, which can lead to a lower reported importance for other features. It would benefit the feature selection process and reduce overfitting for the tree model, however it does not indicate that the feature with lower importance in tree models is also insignificant in statistics. On the contrary, the feature with lower importance may turn out to be equally important as the chosen feature, which can be proven by the obvious difference of feature importance between indoor and outdoor temperature in Figure 9.

By comparison with recursive method RFECV, both RF and RFECV consider and evaluate features in the model altogether and deemed indoor temperature, outdoor temperature, and relative humidity as important features, which verified the validity of feature selection results with each other between these two methods. For Random Forest, the calculated feature importance of each factor actually indicate the reduction of impurity in random forest, which make the feature selection results more explainable compared to RFECV. Besides, RF is much more computationally cheaper because it can avoid recursive process.

4. Conclusions

This study demonstrated both recursive and a non-recursive feature selection methods, which are each capable of considering all influencing factors simultaneously so as to take into account confounding effects among various factors in the prediction of window opening behaviours. Two machine learning algorithms were applied as estimators in the recursive selection process, namely support vector classification (SVC), logistic regression (LR), and one in non-recursive process, a random forest method (RF). A complete feature selection scheme has been demonstrated by the combination of recursive feature elimination (RFE) and recursive feature elimination with cross validation (RFECV). In general, several main conclusions about the feature selection in window behaviour can be made as followed:

(1) Based on the review of current study on window behaviour prediction, three problems exist related to the influencing factors or features in such prediction models: no clear criterion exist to guide the feature selection process; features are separated from each other without a consideration of their confounding effects among features; no comprehensive feature subset search strategy is involved to deal with problems associated with large feature numbers. The status quo of the study of feature selection in window behaviours also manifests the importance and necessity of re-examining the criterion and approach when making decisions on feature selection.

(2) Factors correlate with each other to different degrees, which can make some of factors with high correlations become redundant features in the prediction of window behaviour. The individual feature relevance assessment, which has been applied in previous researches, has limited effects in the elimination of redundant features.

(3) In recursive methods, RFE and RFECV can be combined to solve the window behaviour prediction problems related to abundances of influencing factors. Recursive feature elimination (RFE) can be applied at the preliminary stage to get rid of some less relevant features and reduce the dimensionality of the model when the number of features is relatively high in the collected data. Recursive feature elimination with cross validation (RFECV) can be further employed to search for the most appropriate feature subset by eliminating less relevant features recursively when considering all features together.

(4) The algorithm in the prediction model can demonstrate different prediction accuracies with different feature subsets. Different algorithms can also perform

diversely with same feature subset, although the obtained feature subset results obtain using LR, SVC, and RF are not totally identical, all algorithms have successfully identified indoor temperature, outdoor temperature, and relative humidity as most important features when predicting window behaviour.

(5) Logistic regression (LR) and support vector classification (SVC) demonstrated different traits in recursive feature elimination. LR shows a higher maximum in CV scores while SVC shows a stronger stability during the selecting process. Both of them can be considered efficient in this study due to their similar CV scores. It should be noted that chosen algorithms should remain constant through the feature selection process and model establishing stage. Random forest analysis performs well in eliminating redundant features, for example the low feature importance of outdoor temperature in the results. It is also computationally cheaper compared to recursive methods.

References

D'OCA, S. & HONG, T. 2014. A data-mining approach to discover patterns of window opening and closing behavior in offices. *Building and Environment,* 82, 726-739.

D'OCA, S., FABI, V., CORGNATI, S. P. & ANDERSEN, R. K. 2014. Effect of thermostat and window opening occupant behavior models on energy use in homes. *Building Simulation,* 7, 683-694.

DE SILVA, A. M. & LEONG, P. H. W. 2015. Feature Selection. *Grammar-Based Feature Generation for Time-Series Prediction.*

FABI, V., ANDERSEN, R. V., CORGNATI, S. & OLESEN, B. W. 2012. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment,* 58, 188-198.

FILIPPÍN, C., FLORES LARSEN, S., BEASCOCHEA, A. & LESINO, G. 2005. Response of conventional and energy-saving buildings to design and human dependent factors. *Solar Energy,* 78, 455-470.

FRITSCH, R., KOHLER, A., NYGÅRD-FERGUSON, M. & SCARTEZZINI, J. L. 1990. A stochastic model of user behaviour regarding ventilation. *Building and Environment,* 25(2), 173-181.

GUYON, I. & ELISSEEFF, A. 2003. An Introduction to Variable and Feature Selection. *Journal of Machine Learning Research*.

HAAS, R., AUER, H. & BIERMAYR, P. 1998. The impact of consumer behavior on residential energy demand for space heating. *Energy and Buildings,* 27, 195-205.

HALDI, F. & ROBINSON, D. 2009a. Interactions with window openings by office occupants. *Building and Environment,* 44(12), 2378-2395.

HALDI, F. & ROBINSON, D. 2009b. Interactions with window openings by office occupants. *Building and Environment,* 44, 2378-2395.

HERKEL, S., KNAPP, U. & PFAFFEROTT, J. 2008. Towards a model of user behaviour regarding the manual control of windows in office buildings. *Building and Environment,* 43, 588-600.

LIU, H. & MOTODA, H. 1998. *Feature Selection for Knowledge Discovery and Data Mining*, Kluwer Academic Publishers.

MASOSO, O. T. & GROBLER, L. J. 2010. The dark side of occupants' behaviour on building energy use. *Energy and Buildings,* 42, 173-177.

NICOL, J. F. 2001. Characterising occupant behaviour in buildings: towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans. *Seventh International IBPSA Conference, Rio De Janeiro*, 1073-1078.

PAN, S., XIONG, Y., HAN, Y., ZHANG, X., XIA, L., WEI, S., WU, J. & HAN, M. 2018. A study on influential factors of occupant window-opening behavior in an office building in China. *Building and Environment,* 133, 41-50.

PARYS, W., SAELENS, D. & HENS, H. 2011. Coupling of dynamic building simulation with stochastic modelling of occupant behaviour in offices – a review-based integrated methodology. *Journal of Building Performance Simulation,* 4, 339-358.

SHEN, W., CHUANQI, X., SONG, P. J. S., YUNMO WANG, XIAOYAN LUO, TAREK M HASSAN, & STEVEN FIRTH, F. F., RORY JONES, PIETER DE WILDE 2015. Analysis of factors influencing the modelling of occupant window opening behaviour in an office building in Beijing, China. *Proceedings of BS2015: 14th International Conference of the International Building Performance Simulation Association*.

TSANAS, A. & XIFARA, A. 2012. Accurate quantitative estimation of energy performance of residential buildings using statistical machine learning tools. *Energy and Buildings,* 49, 560-567.

WEI, S., BUSWELL, R. & LOVEDAY, D. 2013. Factors affecting 'end-of-day' window position in a non-air-conditioned office building. *Energy and Buildings,* 62, 87-96.

WEI, S., JONES, R. & DE WILDE, P. 2014. Driving factors for occupant-controlled space heating in residential buildings. *Energy and Buildings,* 70, 36-44.

YAN, D., HONG, T., DONG, B., MAHDAVI, A., D'OCA, S., GAETANI, I. & FENG, X. 2017. IEA EBC Annex 66: Definition and simulation of occupant behavior in buildings. *Energy and Buildings,* 156, 258-270.

Adaptation by coexistence: A comparative study of thermal comfort in individual and shared office spaces in Chile.

Laura Marín-Restrepo[1], Maureen Trebilcock[2] and Jaime Soto-Muñoz[3]

[1] Faculty of Architecture, Construction and Design; University of the Bío-Bío, Chile; lmadim@gmail.com;
[2] Department of Architectural Design and Theory; Faculty of Architecture, Construction and Design; University of the Bío-Bío, Chile; mtrebilc@ubiobio.cl;
[3] Department of Building Sciences; Faculty of Architecture, Construction and Design; University of the Bío-Bío, Chile; jsotom@ubiobio.cl

Abstract: In shared spaces, adaptive actions can be limited by a coexistence factor, which has an impact on thermal expectations. This study aims to compare the perception of thermal comfort, comfort temperature and adaptive actions in individual and shared offices. Fieldwork was carried out in 9 office buildings in Concepción (36°S) and 8 in Santiago (33°S), Chile. In each building, the indoor environment was measured and thermal comfort surveys were administered at 3 different times during a winter day. The comfort temperature calculated showed variations from 0.3 to 1K between individual and shared spaces. In most cases, occupants of individual offices showed a greater preference for thermal variation than occupants of shared ones. Slightly more acceptability was found in individual spaces. Participants performed more adaptive actions in individual versus shared spaces, although this does not imply thermal discomfort. These findings suggest that the occupants of shared spaces have "adapted", since even when their comfort temperature is not equal to the indoor temperature, they declare that they accept the indoor environment and prefer no changes in it. This shows that thermal comfort varies according to the type of space and social constraints, which should be considered in design phase calculations.

Keywords: adaptive thermal comfort, office buildings, social adaptation, social constraints, occupant behaviour

1. Introduction

The adaptive approach assumes that humans use numerous strategies to achieve thermal comfort. They interact with the environment to improve their conditions (Humphreys, Nicol and Roaf, 2016). Therefore, comfort is understood as dynamic rather than a specific condition or already given attribute. The needs and expectations of people are specific; they change according to the context, culture, and climate to which individuals are accustomed. People from different cultures and climates consider themselves to be comfortable in a wide range of temperatures, mainly related to the outdoor temperatures that are normal for them, according to adaptive comfort studies (Nicol, Humphreys and Roaf, 2012).

This approach defines the adaptive model based on the adaptive principle: “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” (Nicol and Humphreys, 2002). The actions related with thermal comfort are usually divided in two groups: those that modify the environment to make it more comfortable and those that allow the occupant to adapt to the environmental conditions (Andersen, 2009). The first group includes opening/closing a window, adjusting solar shading or blinds, using devices like fans or heaters, and changing the set-point of an HVAC system. The second group includes changing clothes and body posture or physical activity adjustment, as well as consuming hot or cold drinks. In this group, psychological mechanisms like tolerating or ignoring the situation may be included, although they are considered less effective and less healthy because they do not solve the problem (Heerwagen and Diamond, 1992). Thus, discomfort is caused or cannot be avoided, by constraints on the range of actions that people can perform in order to adapt the environment or adapt themselves to it, whether by physical, social or other factors.

In this regard, social concerns play an important role in the way that occupants interact with a building and adapt themselves to its conditions (Day and O 'brien, 2017). O'Brien and Gunay (2014) have determined that occupants' behaviour is limited by social influences, since undertaking an adaptive action may bother other occupants. Although some studies have recognized that occupants prefer diverse conditions, shared spaces often impose the requirement that multiple users withstand similar conditions (O'Brien and Gunay, 2014). Particularly in offices, the possibility of personal adaptation without restrictions is considered unsustainable (Chappells and Shove, 2004), due to the incompatibility of the comfort perceptions of several people facing the same environmental conditions. Therefore, thermal conditioning systems are usually calculated in a general way and with the same standards for the whole space. Ideally, the space and its systems would provide the general conditions of comfort, but all occupants would have the ability to adjust the indoor environment to suit their personal needs (Karjalainen, 2013). However, most of the existing controls in shared spaces, such as a light switch and a thermostat per area, make that adjustment difficult (O'Brien and Gunay, 2014). These situations reflect the way in which offices are currently designed and operated.

Nowadays, most office spaces are conceived of as open due to work dynamics. Nevertheless, in general occupant behaviour models do not distinguish between single occupation and multiple occupation spaces (Fabi *et al.*, 2012; Yan *et al.*, 2015; Hong *et al.*, 2016, 2017), most likely because when there is more than one person in a space, social interactions are still far from being understood (O'Brien and Gunay, 2014; Schweiker and Wagner, 2016; Schweiker, 2017).

Nonetheless, some studies have shown that occupant satisfaction decreases with a greater number of people in an office (Karjalainen, 2013). Hedge *et al.* (1989) found negative correlations between the type of office, the perceived environmental control, and the perceived environmental conditions. Brager, Paliaga and de Dear (2004) have also shown the negative effect of perceived reduced control on satisfaction with thermal conditions (Schweiker and Wagner, 2016). In this sense, numerous studies have reported that occupants are more comfortable in private offices than in open plan offices (Heerwagen and Diamond, 1992; Leaman A., 2010; Bluyssen, Aries and van Dommelen, 2011; Frontczak *et al.*, 2012). Similarly, Heerwagen y Diamond (1992) found that occupants in individual offices made more environmental or behavioural changes to achieve comfort, while occupants of open spaces relied more on psychological coping mechanisms such as tolerating or ignoring discomfort.

Accordingly, it could be expected that individual and shared spaces have different thermal performances and produce diverse perceptions of thermal comfort since coexisting would imply a restriction in adaptive actions. Although the differences have been noted additional knowledge is still needed on how individual behaviour patterns change in the presence of others (Schweiker and Wagner, 2016). Likewise, at present comfort requirements appear to be independent of the type of space. Thus, it is important to ask if these have any influence on the adaptive process and if it is necessary to distinguish between individual and shared spaces when thermal comfort is studied. Are the requirements different? What implications would this have on the design process? Therefore, this paper aims to compare thermal comfort perception (thermal sensation, preference and acceptability), comfort temperature, and adaptive actions in individual and shared offices to identify differences in the adaptive process.

2. Methodology

On-site fieldwork including a thermal comfort survey with simultaneous measurements of environmental conditions was carried out in the two main cities of Chile: Santiago (33°S) and Concepción (36°S). These cities present different climatic conditions, thermal conditioning strategies and adaptation opportunities. Concepción has a temperate climate with no extreme winters or summers. During the winter, it is common to use some type of heating, whereas in the summer only some buildings use cooling, which normally operates in mixed-mode, that is, some of the time, in some areas of the space, or simultaneously with natural ventilation. Passive adaptive opportunities are commonly used. Santiago has colder winters and hotter summers, so most of the office buildings are fully air-conditioned and do not have operable windows, thereby offering fewer opportunities for adaptation, which mainly involve the adjustment of thermostats.

2.1. The buildings

The study includes 9 office buildings in Concepción and 8 in Santiago, which were selected according to the following criteria:

- Construction after 1995
- A variety of HVAC systems and adaptation opportunities
- Easy access for the research team

Table 1 summarizes the cases studied and their main characteristics. In each building, one or two floors were selected for the study, according to the access granted by the companies that work in them.

Table 1. Study cases and their characteristics

	Case	Year built	Total Floors	Studied floors	Operable windows	HVAC system	Control type	Central heating
Concepción	A	2016	6	2 and 3	Yes	Some areas	Thermostat	Some areas
	B	2016	2	1 and 2	Yes	Yes	Thermostat	No
	C	2016	8	4 and 7	Yes	Yes	Remote control	No
	D	2005	6	3 and 6	Yes	Yes	Thermostat	No
	E	2016	2	1 and 2	Yes	Yes	Thermostat	No
	F	2013	13	2 and 9	Some areas	Yes	Thermostat	No
	G	2015	16	6	Yes	Yes	Thermostat	No
	H	2009	3	1	Yes	No	N/A	Yes
	I	2013	2	1 and 2	Some areas	Yes	Remote control	No
Santiago	J	2009	17	2 and 3	No	Yes	Thermostat	No
	K	2016	13	12	No	Yes	Thermostat	No
	M	2016	11	6	No	Yes	Thermostat	No
	N	1997	14	9	Yes	Yes	Thermostat	No
	P	2016	10	3 and 5	No	Yes	Thermostat	No
	Q	2006	22	18	No	Yes	Thermostat	No
	R	1995	22	15	No	Yes	Thermostat	No
	S	2000	30	4	No	Yes	Thermostat	No

In each case, the studied areas were classified according to the type of space: shared open plan (SO) and shared enclosed spaces (between 2 and 8 people) (SE), and individual spaces (IN). Although the first two types are shared offices, they are differentiated because of the level of control and adaptation opportunities that a smaller space can provide. Figure 1 illustrates the space types.

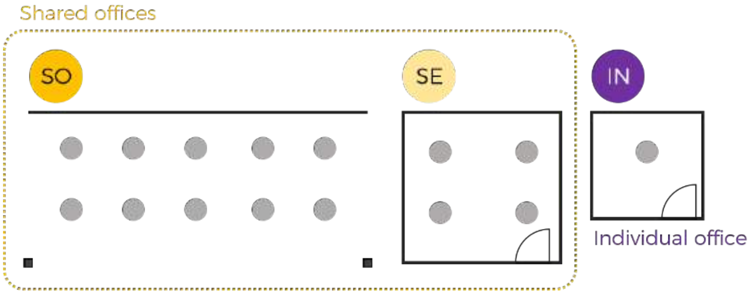


Figure 1. Office types

2.2. Fieldwork

This investigation is part of a larger research project that involved fieldwork in winter, spring and summer. However, the results presented in this paper correspond only to the winter season (July and August 2017).

Thermal comfort surveys were conducted face-to-face 3 times during a single day in each case: morning (between 8:30 and 10:30), noon (between 12:00 and 1:00) and late afternoon (between 16:00 and 18:00). The equipment measuring the indoor environmental conditions was installed at the beginning of each building´s work day (usually 8:00) and removed after the late afternoon surveys. In the first survey, an occupant characterization section was included in which the type of office was identified. This information is later contrasted with the architectural plans of each building.

Data collection was performed by a team of researchers and students. Table 2 shows the number of participants (subjects) and the total datasets obtained, by space type.

Table 2. Total datasets and subjects by office type

	Concepción		Santiago	
Office type	**Datasets**	**Subjects**	**Datasets**	**Subjects**
SO	558	211	904	351
SE	207	79	96	37
IN	76	32	41	18
Total	841	332	1041	406

SO: Shared offices (open plan), SE: Shared enclosed spaces, IN: Individual spaces

2.3. Thermal comfort survey

The survey was conducted in Spanish and included:

- Thermal sensation (TS), measured using a seven-point scale ranging from hot (+3) to cold (-3), with neutral (0) in the centre. The Spanish versions of ASHRAE 55 and EN-ISO 15251 were reviewed and taken as reference, but a panel of experts from the Chilean context found that the language was not accurate with regards to the daily life of Chileans. Therefore, an adjusted Spanish translation was used based on ASHRAE 55 in English.
- Thermal preference (TP), using a five-point scale (Nicol, Humphreys and Roaf, 2012; Indraganti *et al.*, 2014).
- Thermal acceptability (TA), with a binary input (Indraganti *et al.*, 2014; Forgiarini Rupp and Ghisi, 2017).
- Adaptive actions and opportunities.

Table 3 shows the scales used in the questionnaire for questions 1 to 3, and Figure 2 shows the question about the actions and opportunities for modification of the environment.

Table 3. Thermal comfort scales used

Scale value	Description of scale		
	Thermal sensation (TS)	**Thermal preference (TP)**	**Thermal acceptability (TA)**
3	Hot		
2	Warm	Much warmer	
1	Slightly warm	A bit warmer	Acceptable
0	Neutral	No change	Unacceptable
-1	Slightly cool	A bit cooler	
-2	Cool	Much cooler	
-3	Cold		

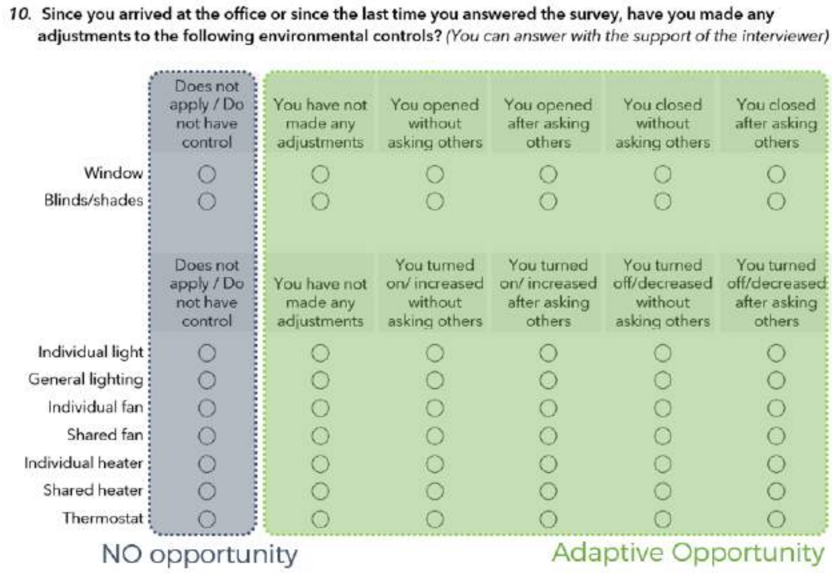


Figure 2. Question about occupant actions related to environmental controls. *Please be aware that the survey was carried out in Spanish.*

The answers to the question shown in Figure 2 determine if an occupant has an adaptive opportunity or not. Environmental controls were related to an adaptive action as shown in Figure 3.

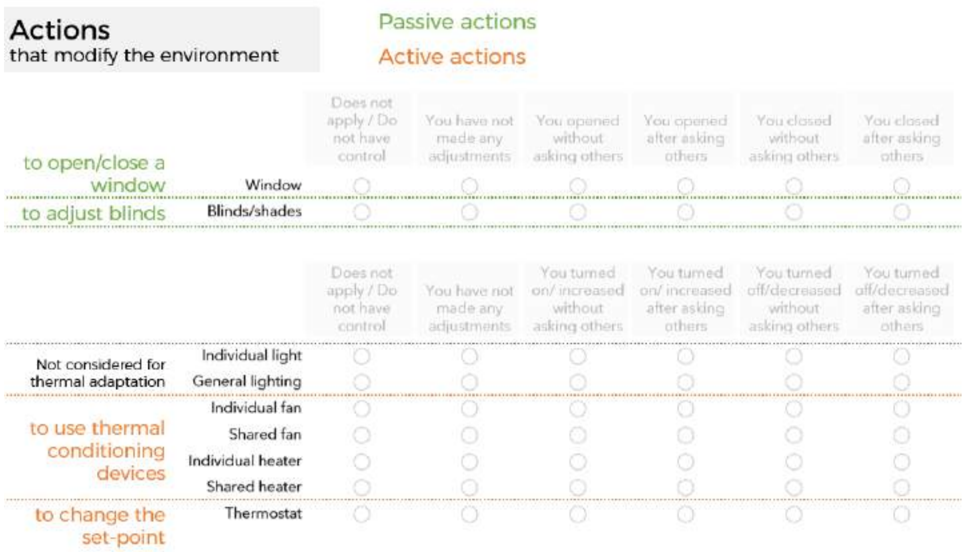


Figure 3. Actions that modify the environment by controls used

2.4. Measurement instruments

The indoor environmental variables (air temperature, globe temperature (T_g), relative humidity and air velocity) were recorded at 1-minute intervals throughout the day with Delta Ohm Datalogger WBGT-PMV-PPD Index equipment.

3. Results

3.1. Environmental conditions

The outdoor temperature in Concepción remained at 13.1 °C on average, varying from 4.5 °C to 18.9 °C during the occupation time of the buildings. Santiago had a mean outdoor temperature of 17.2 °C, varying from 9.6 °C to 23 °C. Mean indoor temperature in Concepción was 21.5 °C, with temperatures between 16 °C and 25.5 °C during occupation hours. Santiago had a mean indoor temperature of 22.5 °C, varying between 16.8 °C and 26.3 °C.

Table 4 summarizes the outdoor and indoor environmental conditions during the fieldwork by office type. It can be observed that on average the individual offices (IN) had a lower globe temperature than the shared ones (SO and SE) in both cities.

Table 4. Indoor and outdoor environmental variables measured

	Concepción											
	SO *(Open plan offices)*				**SE** *(Closed shared offices)*				**IN** *(Individual offices)*			
Variable	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
T_o (°C)	13.0	2.76	4.5	18.9	13.3	2.61	4.5	16.6	13.3	2.78	4.5	18.4
T_g (°C)	21.6	1.45	17.7	24.5	21.6	1.70	17.1	25.5	20.8	1.45	16	24.1
Sample size (N)	558				207				76			

	Santiago											
	SO *(Open plan offices)*				**SE** *(Closed shared offices)*				**IN** *(Individual offices)*			
Variable	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
T_o (°C)	17.5	4.67	9.66	23.1	14.9	5.42	9.66	23	16.0	4.85	9.66	23.1
T_g (°C)	22.6	1.29	19.2	25.4	22.3	1.88	16.8	26.3	22.2	1.21	18.7	24.6
Sample size (N)	904				96				41			

T_o: Outdoor mean temperature in surveyed periods (°C), T_g: Indoor globe temperature (°C).

3.2. Subjective thermal responses

The mean values of the thermal sensation (TS), thermal preference (TP) and thermal acceptability (TA), by type of office for Concepción and Santiago can be found in Table 5 and Table 6, respectively. Figure 4 compares all mean data.

Table 5. Thermal responses Concepción

	Concepción											
	SO *(Open plan offices)*				**SE** *(Closed shared offices)*				**IN** *(Individual offices)*			
Variable	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
Thermal sensation	0.32	1.59	-3	3	0.41	1.60	-3	3	0.13	1.47	-3	3
Thermal preference	0.09	0.84	-2	2	0.11	0.87	-2	2	0.32	0.72	-1	2
Thermal acceptability	0.87	0.33	0	1	0.88	0.32	0	1	0.92	0.27	0	1
Sample size (N)	558				207				76			

Table 6. Thermal responses Santiago

	Santiago											
	SO *(Open plan offices)*				**SE** *(Closed shared offices)*				**IN** *(Individual offices)*			
Variable	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
Thermal sensation	0.35	1.35	-3	3	0.17	1.34	-3	3	-0.34	1.06	-3	2
Thermal preference	-0.11	0.77	-2	2	-0.04	0.78	-2	2	0.32	0.65	-1	1
Thermal acceptability	0.89	0.31	0	1	0.95	0.22	0	1	0.93	0.26	0	1

Sample size (N)	904	96	41

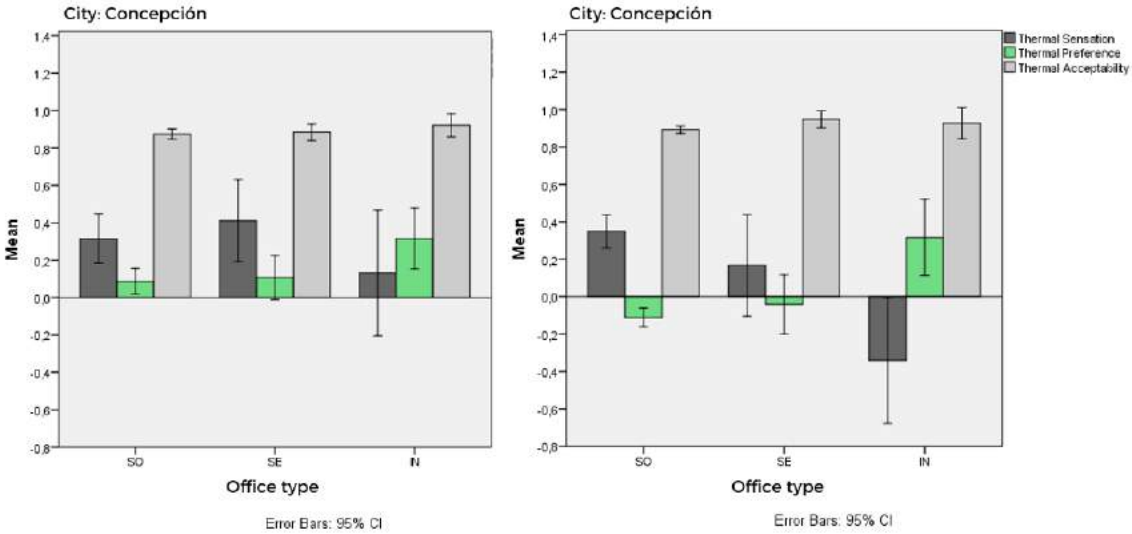


Figure 4. Mean thermal sensation, preference and acceptability

In Concepción, the mean TS vote was higher in relation to the neutral point in shared (SO and SE) than in individual offices (IN). Figure 5 shows that in the shared offices the thermal sensation had a left-skewed distribution, indicating a trend towards the warm side of the scale. In the individual ones, thermal sensation was close to zero, which could be related to the difference in the indoor temperature recorded in the spaces (SO and SE: 21.6 °C, IN: 20.8 °C, see Table 4). Since TS votes between -1 and 1 are usually considered as comfortable, 59% of the respondents would be comfortable in the open plan offices (SO), 56% in the enclosed ones (SE), and 68% in the individual offices (IN).

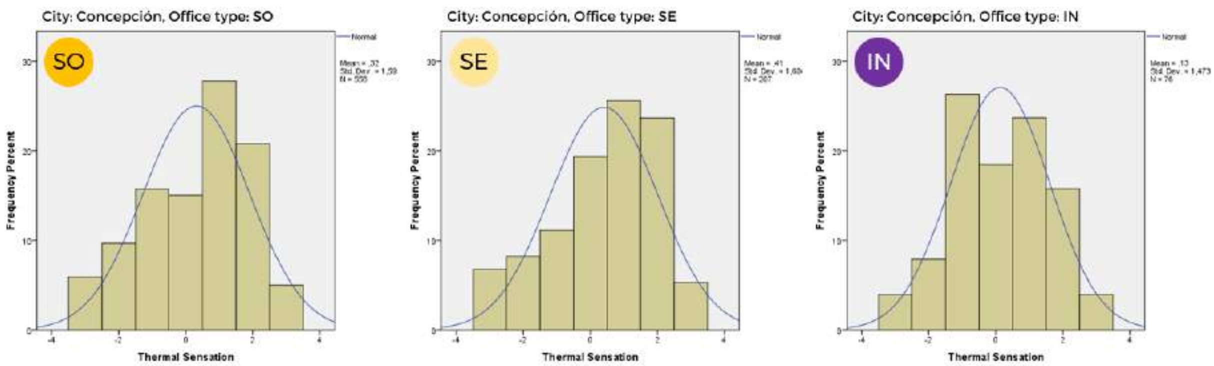


Figure 5. Distribution of subjective thermal sensation Concepción

In Santiago, the three offices types showed different thermal sensations. On average, in SO the thermal sensation was slightly warm, in SE it was close to neutral, while in IN the thermal sensation was slightly cold. In this city, the mean temperatures recorded were very similar (Table 4), thereby suggesting diverse thermal expectations. The TS distribution can be seen in Figure 6. Regarding the votes ranging from -1 to 1, 72% of the respondents would be comfortable in the SO, 74% in the SE, and 88% in the IN.

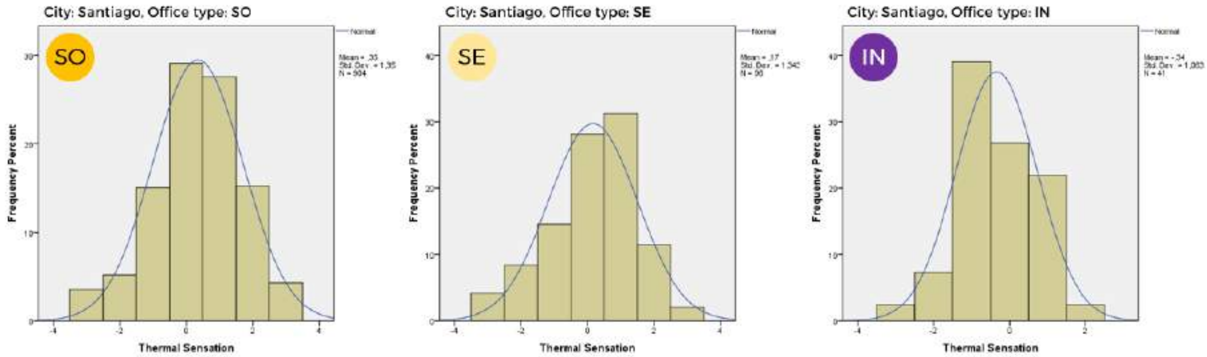


Figure 6. Distribution of subjective thermal sensation Santiago

In both cities, the mean TP vote was closer to zero in the shared offices (SO and SE), thus indicating a greater preference for no change in the thermal conditions. In the individual offices, TP was slightly greater than zero, signalling a preference for warmer environments both in Concepción and Santiago, as shown by the distributions in Figure 7 and Figure 8. Nevertheless, if only the votes that prefer to maintain the thermal conditions (TP = 0) are considered, that is, SO: 43%, SE: 40% and IN: 51% in Concepción; and SO: 47%, SE: 49% and IN: 49% in Santiago, it can be noticed that in more than half of the SO and SE cases, the occupants would prefer to change the environment, which shows that the mean is the result of the normal distribution.

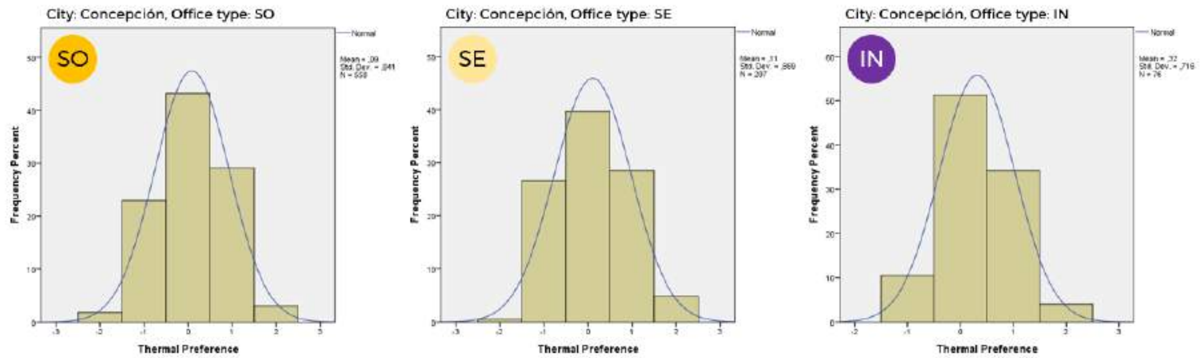


Figure 7. Distribution of subjective thermal preference Concepción

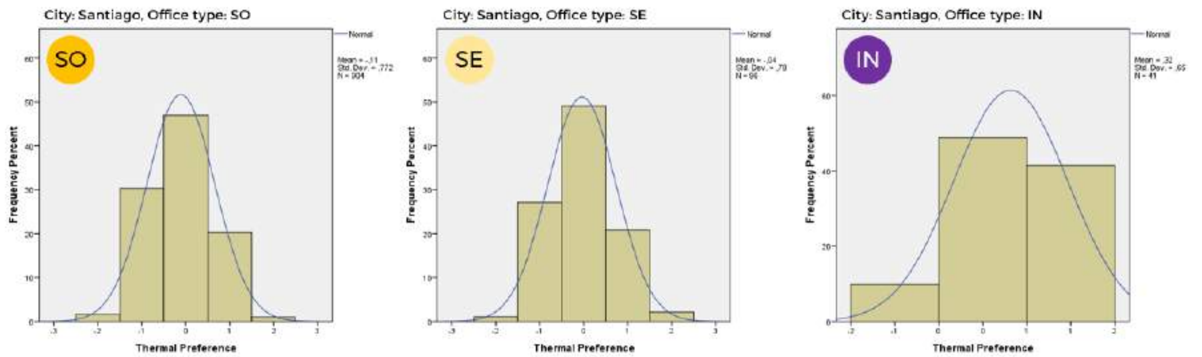


Figure 8. Distribution of subjective thermal preference Santiago

Regarding acceptability, in both Concepción and Santiago, thermal acceptability was lower in SO. In Concepción, individual spaces had the highest acceptability, while in Santiago it was in SE. Despite this, in general the spaces were found to be thermally acceptable, since this variable was always higher than 85%, as shown in Figure 9 and Figure 10.

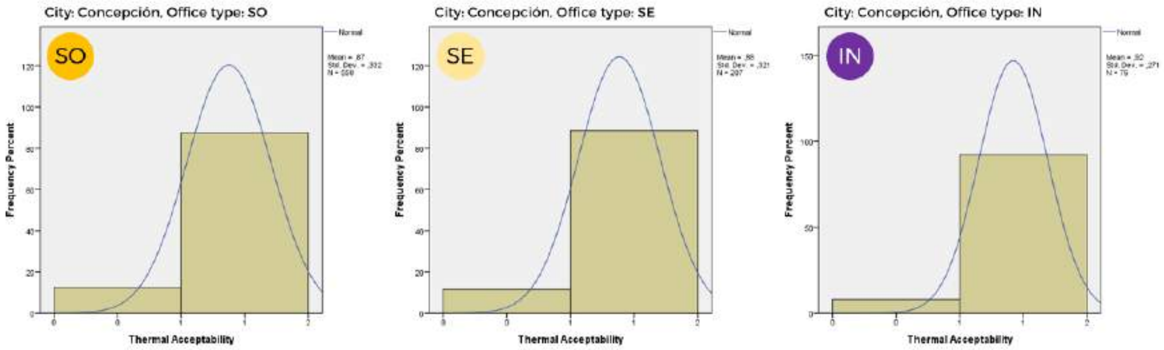


Figure 9. Distribution of subjective thermal acceptability Concepción

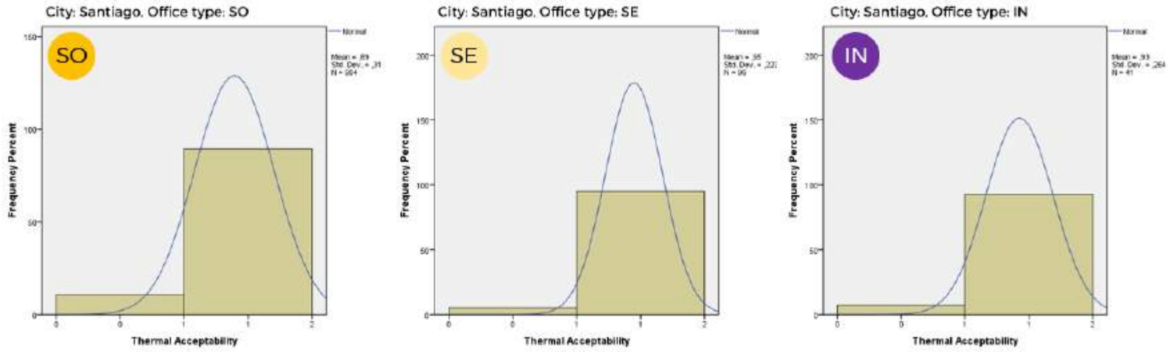


Figure 10. Distribution of subjective thermal acceptability Santiago

It is important to highlight that although in the shared spaces a high proportion of the thermal sensation votes was outside the range defined as comfortable (Concepción SO: 41%, SE: 44%; and Santiago SO: 28%, SE: 26%) and in about half of the cases a variation in the thermal environment is preferred, acceptability is high. This suggests that conditions with votes between ±3 and ±2 are not necessarily uncomfortable in shared spaces, even if there is a preference for adjusting them.

3.3. Comfort temperature

Figure 11 presents the plot of the thermal sensation votes and the globe temperature for each city. The votes were differentiated according to the type of office. As the figure shows, the model generated by the linear regression method is not representative, as it has a small R^2 probably due to sample size.

Consequently, the comfort temperature was calculated using the Griffiths method that considers the size of the sample and because the surveys were conducted on different days with varying environmental conditions. Equation 1 was used.

$$T_{comf} = T_g - (TS - 0)/G \qquad \text{Equation 1}$$

where T_{comf} is the Griffith's comfort temperature (◦C), T_g is the indoor globe temperature (◦C), TS is the sensation vote and G is the Griffith's slope (K^{-1}). The '0' indicates the scale value for 'neutral' sensation. The Griffith's coefficient used was 0.5 K^{-1}, as stipulated by Nicol, Humphreys and Roaf (2012), which represents a 2K rise per unit perturbation in the sensation vote (Indraganti, Ooka and Rijal, 2015).

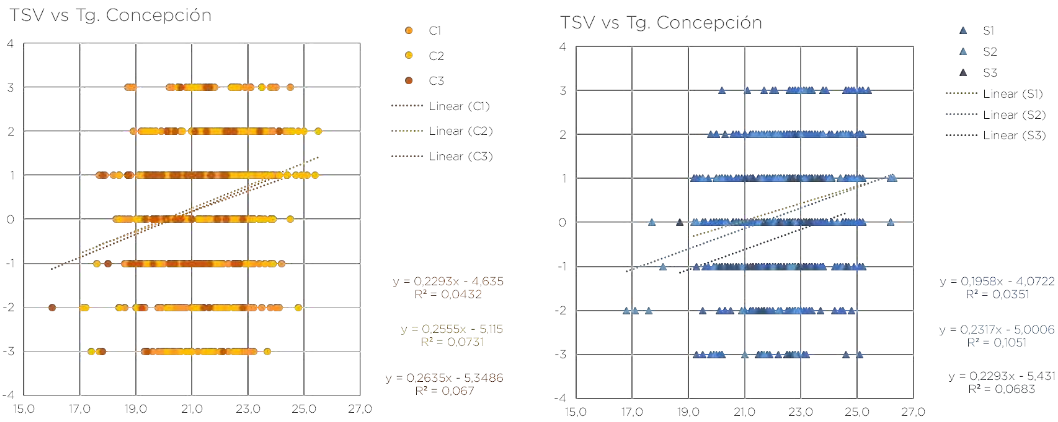


Figure 11. Thermal Sensation and globe temperature cloud

The comfort temperatures calculated for Concepción and Santiago are presented in Table 7 and Table 8, respectively.

Table 7. Comfort temperature Concepción

	Concepción											
	SO ***(Open plan offices)***				**SE** ***(Closed shared offices)***				**IN** ***(Individual offices)***			
Variable	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
T comf (Griffiths)	21.0	3.22	12.7	29.2	20.8	3.20	14.5	29.7	20.5	2.93	14.6	28.1
Tg (°C)	21.6	1.45	17.7	24.5	21.6	1.70	17.1	25.5	20.8	1.45	16	24.1
Tdiff	0.6				0.8				0.3			
Sample size (N)	558				207				76			

Table 8. Comfort temperature Santiago

	Santiago											
	SO ***(Open plan offices)***				**SE** ***(Closed shared offices)***				**IN** ***(Individual offices)***			
Variable	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
T comf (Griffiths)	21.9	2.77	14.2	31.1	22.0	2.73	17	28.8	22.9	2.15	18.7	28.6
Tg (°C)	22.6	1.29	19.2	25.4	22.3	1.88	16.8	26.3	22.2	1.21	18.7	24.6
Tdiff	0.7				0.3				-0.7			
Sample size (N)	904				96				41			

The difference between the globe temperature and the comfort temperature (Figure 12) is an indicator of the possible discomfort in a space: the larger the difference, the greater the expected discomfort (Indraganti *et al.*, 2014).

$$T_{diff} = T_g - T_{comf} \qquad \text{Equation 2}$$

The results of Equation 3 are also presented in Table 7 and Table 8, and indicate the following. On the one hand, in Concepción individual spaces have a comfort temperature closer to the indoor temperature, and in general have more comfortable conditions. Furthermore, it was observed that on the whole, the temperature of the spaces is above the comfort temperature. Since the measurements correspond to the winter season, this could suggest overheating in the spaces.

On the other hand, in Santiago the shared enclosed spaces (SE) have the best conditions, as evidenced by the smallest difference between comfort temperature and globe temperature. Meanwhile, a large difference was found between the comfort temperature of the open plan offices (SO) and the individual ones (IN), which have quite similar globe temperature conditions: in SO, the calculation indicates that occupants would be comfortable with 0.7K less than the actual temperature, while in the IN, the neutral temperature would be 0.7K more. This means that at the same globe temperature, in SO occupants would like to be cooler and in IN warmer. As in Concepción, the shared offices in Santiago are slightly warmer than desired, whereas in the individual offices, according to the perception of the users, the spaces are slightly cooler.

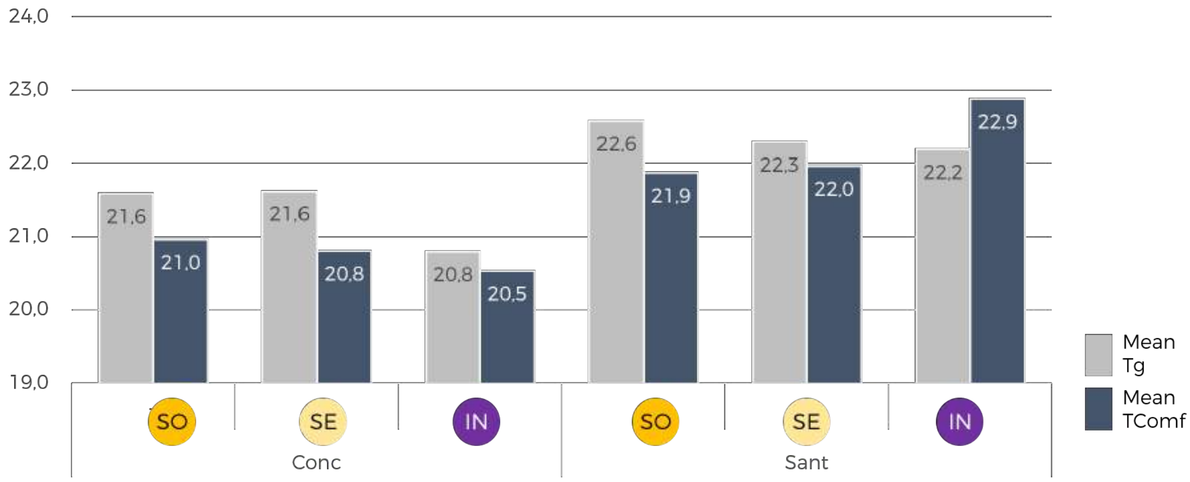


Figure 12. Globe temperature (Tg) and comfort temperature (TComf)

3.4. Opportunities and adaptive actions

As shown Figure 3, the control elements that were included in the survey are categorized into 4 groups according to the type of action they involve: 1. to open/close a window (window); 2. to adjust the solar shading or blinds (blinds/shades); 3. to use thermal conditioning devices (individual and/or shared fans, individual and/or shared heater); and 4. to change the set-point of an HVAC system (thermostat). Consequently, each occupant has 4 possible adaptive opportunities to modify the environment.

In order to define which opportunities each occupant has; an opportunity is considered to exist when the survey response is different from "Does not apply/Do not have control" (Figure 2). This information was contrasted with the architectural plans of the spaces and field observations. The general opportunity level by type of space (Figure 13) is defined according to the accumulated opportunity level of its occupants.

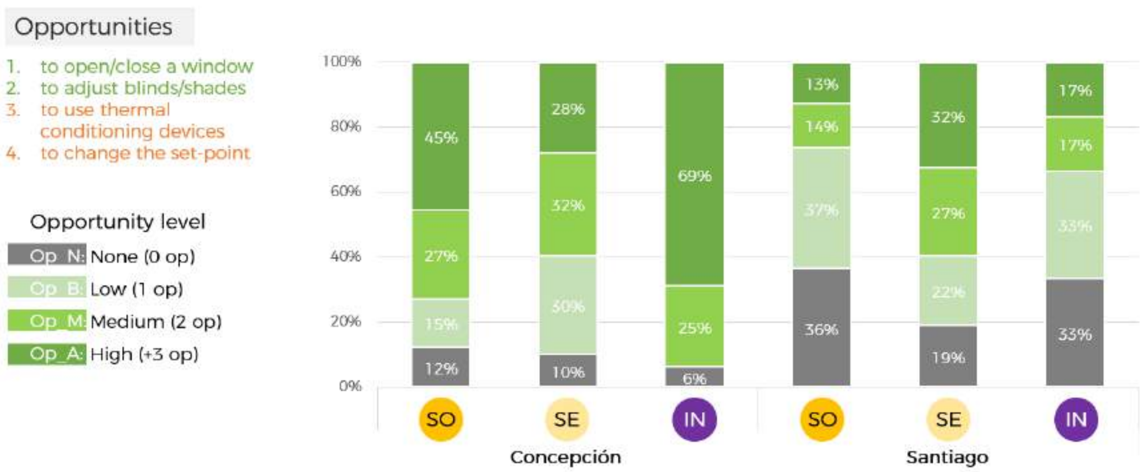


Figure 13. Opportunity level by office type

It can be observed that in Concepción, individual offices have a higher level of opportunity (94%), while only 6% of IN cases have no type of adaptive opportunity related to the environment. In addition, 69% of people in individual spaces have a high opportunity level, that is, more than 3 adaptation options. Likewise, more than 78% of the occupants in the shared spaces have in general at least one opportunity, and more than 50% two or more. Only 12% of the SO cases and 10 % of SE do not have opportunities.

On the contrary, in Santiago adaptation opportunities are generally lower. In SO, 36% of occupants do not have opportunities and in IN, 33%. In addition, only 13% in SO and 17% in IN have more than 3 opportunities. The best conditions are in SE, which have the lowest null opportunity rate, with only 19% of the occupants without any opportunities, and 32% with more than 3 opportunities.

This shows that there are different levels of opportunity according to the space type and city. In Concepción, it is clear that individual offices have more opportunities, but in Santiago there is not a big difference between office type, most likely because of the kinds of opportunities offered by Santiago buildings (Figure 14).

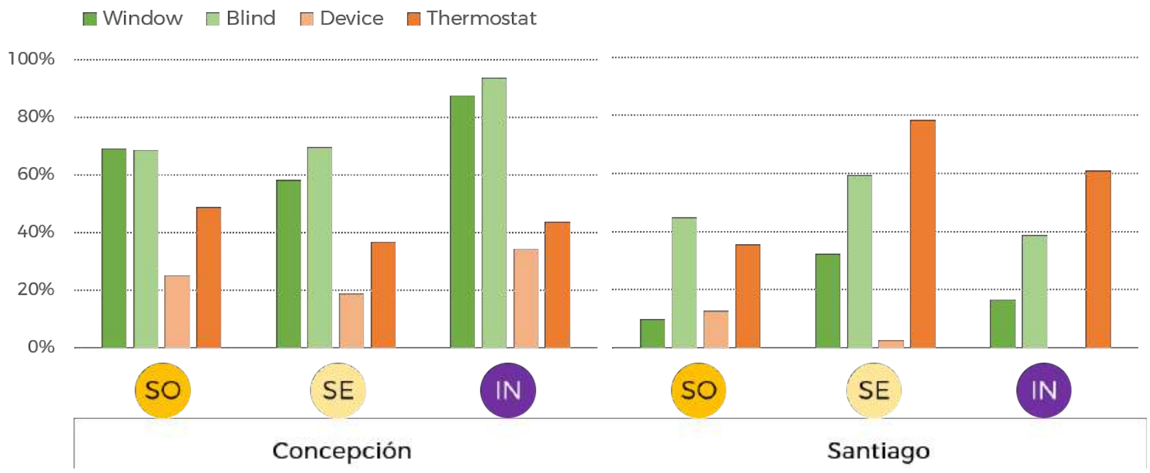


Figure 14. Opportunity type (% total participants)

Subsequently, possible interaction of the controls associated with the available opportunities (Figure 3) was examined based on the survey responses. Figure 15 shows the relationship between all of the surveys and those in which some action took place. It can be observed that in both cities the shared offices registered the least interaction.

Figure 16 presents the actions performed. In Concepción, all the kinds of opportunities were used, including the operation of windows even though it was winter. In the individual offices, interaction was greater, and mostly involved the blinds, the thermostat and devices such as heaters. In SO, the main action involved the blinds, followed by the use of thermal devices. Setting the thermostat was the least used action. Overall, in Concepción more actions were carried out in all the spaces, compared to Santiago.

In Santiago, the actions were mainly concentrated in the thermostat, as well as in the blinds, as those are the most readily available controls. It seems that fewer actions were taken in the open offices (SO), especially those related to the thermostat. It is worth noting that in individual offices, actions with thermal devices such as heaters were not performed.

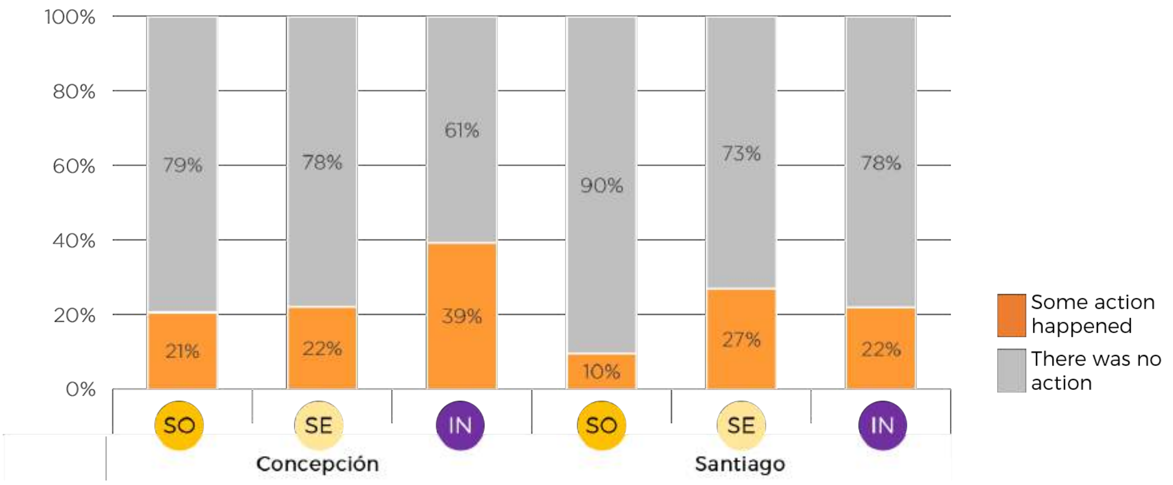


Figure 15. Relationship between all of the surveys and those in which some action took place

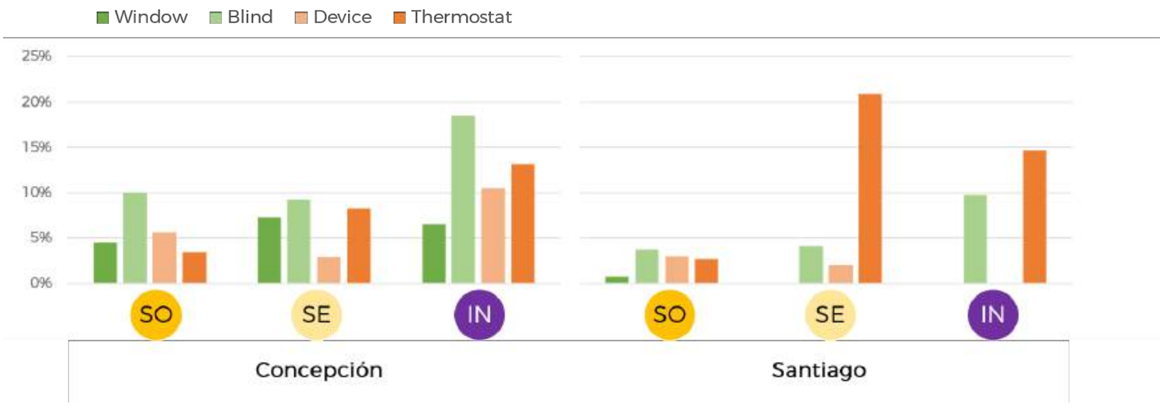


Figure 16. Actions performed (total actions/total surveys)

4. Discussion

The adaptive principle suggests that if adaptation has occurred, the comfort temperature should be equal to the indoor temperature of a space (Nicol, Humphreys and Roaf, 2012). The present study shows that on average in all office types, the comfort temperature was quite close to the interior temperature, with a maximum difference of 0.8K. However, differences were found among office types, thus showing that their occupants have varying thermal requirements. High acceptability of thermal conditions was found. Although, when reviewing the data collected in detail, differences between individual and shared offices were observed, particularly in the adaptation measures that were carried out.

Heerwagen and Diamond (1992) proposed "inaction" as a psychological mechanism of response to discomfort. They found that the occupants of private offices made more environmental or behavioural changes to regain comfort, while the occupants of open spaces relied more on psychological coping mechanisms such as tolerating or ignoring discomfort. However, they could not determine if people acted in this way because there were no other options or because other actions did not work out, and considered that this kind of adaptive measure is unlikely to be effective because it does not solve the problem.

In the present study, people in shared offices declared that they accepted the environment and did not want to modify it, which may indeed suggest that adaptation of this type could be effective in the long term. Therefore, this adaptation should not be understood as "tolerating" or "ignoring", but rather as a change in the thermal pattern, similar to the way a foreigner becomes used to a city in a new country.

This makes sense if we understand adaptation as a set of learning processes and consider that people adapt well to their usual environments (Nicol, Humphreys and Roaf, 2012). Adaptation is a gradual loss of the human response to repeated thermal stimuli; it can be physiological, psychological or behavioural (de Dear, R; Brager, 1998); and is linked not only to the climatic environment, but also to the social environment, as the findings presented in this article suggest. In this way, "adaptation by coexistence" is proposed, where people who share spaces decrease their thermal expectations.

As in this research, others have observed that the frequency of adaptive actions decreases significantly in shared spaces compared to private offices (Galasiu and Veitch, 2006; Leaman A., 2010; Fabi, Andersen and Corgnati, 2011). This has been attributed to the reluctance of individuals to undertake an adaptive measure that can eventually bother other occupants (O'Brien and Gunay, 2014). Nevertheless, the differences found between shared and individual offices in the present study also suggest that the absence of actions in shared space does not necessarily represent thermal discomfort.

Similarly, Schweiker y Wagner (2016) indicate that with a greater number of people in the same room, perceived control as well as neutral temperatures are negatively affected. Actions on windows increase, but actions on blinds and fans are minimized. This is interesting because, "although satisfaction with conditions is lower, the actions that would potentially improve these conditions are less realized" (Schweiker and Wagner, 2016). On the contrary, the present study found high values of acceptability. This could be due to the type of research: whereas Schweiker and Wagner conducted their study in an experimental manner, the present research was carried out in the field. Thus, the high acceptability found could be the result of long-term adaptation that an experimental study might not reproduce.

Haldi and Robinson (2011) discovered that the occupants of individual offices closed the blinds in a much lower working plane illumination threshold than in shared offices, which is comparable with the findings of the present research with regards to thermal issues: comfort temperatures are different depending on the office type, and this is a factor to take into account when defining parameters or boundary thermal conditions for spaces.

Although the differences are not statistically significant, it is important to note that conditions, requirements and perceptions differ between shared and individual spaces, and therefore further research is needed on the subject. Some limitations of this study were the size of the sample by office type and that it only included one season. In addition, data collection was not performed simultaneously, due to logistical restrictions. Nevertheless, the findings suggest interesting aspects to be reviewed. Currently the authors are examining the problem from a longitudinal point of view, including spring and summer data.

5. Conclusions

The findings presented show:

1. In Concepción, the subjective thermal sensation tends to be closer to neutral in individual spaces than in shared spaces. Hence, the calculated comfort temperature is more similar to the indoor temperature. In Santiago, the spaces with the comfort temperature closest to the indoor temperature were the shared closed offices (SE). There was a difference of 1K between the comfort temperature in open plan offices (SO) and individual spaces (IN), with the same indoor temperature.

2. There is a greater preference to preserve the environment without changes in shared spaces, while in individual spaces more modifications are preferred.
3. Thermal environments are generally accepted, although there is slightly more acceptability in individual spaces.
4. People perform more adaptive actions in individual spaces than in shared spaces, since they do not have the social constraints involved in sharing space. However, this does not imply thermal discomfort.

This suggests that in some way the occupants of shared spaces have "adapted" to their context and social constraints, since even when their calculated comfort temperature is not equal to the indoor temperature, they declare that they accept the indoor environment and prefer no changes in it. This could mean a wider spectrum in the comfort range of the occupants of shared spaces and in this way "adaptation by coexistence" is proposed.

The presented results correspond only to one season. Although trends were identified, it is necessary to analyse data collected during the spring or fall and summer seasons in order to validate the findings.

In agreement with other studies carried out, the results highlight the importance of specific studies of thermal comfort according to contextual factors, especially in the growing research area of models of occupant behaviour, which seeks to improve the environmental performance predictions of buildings from the design phase by incorporating occupant behaviour into simulations. Although the adaptive approach does not seek to predict exactly which temperatures are comfortable but rather obtain inputs that make it possible to generate spaces that are flexible to the adaptability of the occupants, knowing the conditions and constraints under which occupants behave is useful for a more tailored design that coincides better with reality and strives for greater user well-being while optimizing energy use.

6. Acknowledgements

This research is part of Fondecyt Project 1171497. We thank all the survey participants, the companies for allowing the study, the research team and students who conducted the data collection and Rodrigo Figueroa, researcher in charge of the measuring equipment. The authors also acknowledge Rodrigo Herrera, anthropologist, for his support and contribution to the research from a social perspective.

7. References

Andersen, R. K. (2009) *Occupant behaviour with regard to control of the indoor environment*. Technical University of Denmark. Available at: http://orbit.dtu.dk/services/downloadRegister/5044630/Thesis with papers - RVA.pdf.

Bluyssen, P. M., Aries, M. and van Dommelen, P. (2011) 'Comfort of workers in office buildings: The European HOPE project', *Building and Environment*. Pergamon, 46(1), pp. 280–288. doi: 10.1016/J.BUILDENV.2010.07.024.

Brager, G. S., Paliaga, G. and de Dear, R. (2004) 'Operable Windows, Personal Control and comfort', *ASHRAE Transactions*, 110, pp. 1–20.

Chappells, H. and Shove, E. (2004) 'COMFORT: A review of philosophies and paradigms'.

Day, J. K. and O 'brien, W. (2017) 'Oh behave! Survey stories and lessons learned from building occupants in high-performance buildings', *Energy Research & Social Science*. Elsevier, (August), pp. 1–0. doi: 10.1016/j.erss.2017.05.037.

de Dear, R; Brager, G. (1998) 'Developing an Adaptive Model of Thermal Comfort and Preference'.

Fabi, V. *et al.* (2012) 'Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models', *Building and Environment*. Elsevier Ltd, 58, pp. 188–198. doi: 10.1016/j.buildenv.2012.07.009.

Fabi, V., Andersen, R. and Corgnati, S. (2011) ‘Description of occupant behaviour in building energy simulation: state-of-art and concepts for improvements’, *Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November*, pp. 2882–2889. Available at: http://ibpsa.org/proceedings/BS2011/P_1923.pdf.

Forgiarini Rupp, R. and Ghisi, E. (2017) ‘Predicting thermal comfort in office buildings in a Brazilian temperate and humid climate’, *Energy and Buildings*. Elsevier B.V., 144, pp. 152–166. doi: 10.1016/j.enbuild.2017.03.039.

Frontczak, M. *et al.* (2012) ‘Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design’, *Indoor Air*. Blackwell Publishing Ltd, 22(2), pp. 119–131. doi: 10.1111/j.1600-0668.2011.00745.x.

Galasiu, A. D. and Veitch, J. A. (2006) ‘Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review’, *Energy and Buildings*. Elsevier, 38(7), pp. 728–742. doi: 10.1016/J.ENBUILD.2006.03.001.

Haldi, F. and Robinson, D. (2011) ‘Modelling occupants’ personal characteristics for thermal comfort prediction’, *International Journal of Biometeorology*, 55(5), pp. 681–694. doi: 10.1007/s00484-010-0383-4.

Hedge, A. *et al.* (1989) ‘Work-related illness in offices: A proposed model of the “sick building syndrome”’, *Environment International*, 15(1–6), pp. 143–158. doi: 10.1016/0160-4120(89)90020-2.

Heerwagen, J. and Diamond, R. (1992) ‘Adaptations and Coping: Occupant Response to Discomfort in Energy Efficient Buildings’, in *1992 Summer Study on Energy Efficiency in Buildings*. Washington DC: American Council for an Energy Efficient Economy, pp. 83–90.

Hong, T. *et al.* (2016) ‘Advances in research and applications of energy-related occupant behavior in buildings’, *Energy and Buildings*. Elsevier B.V., 116, pp. 694–702. doi: 10.1016/j.enbuild.2015.11.052.

Hong, T. *et al.* (2017) ‘Ten questions concerning occupant behavior in buildings: The big picture’, *Building and Environment*, 114, pp. 518–530. doi: 10.1016/j.buildenv.2016.12.006.

Humphreys, M., Nicol, F. and Roaf, S. (2016) *Adaptive thermal comfort : foundations and analysis*. 1st edn.

Indraganti, M. *et al.* (2014) ‘Adaptive model of thermal comfort for offices in hot and humid climates of India’, *Building and Environment*. Elsevier Ltd, 74(January), pp. 39–53. doi: 10.1016/j.buildenv.2014.01.002.

Indraganti, M., Ooka, R. and Rijal, H. B. (2015) ‘Thermal comfort in offices in India: Behavioral adaptation and the effect of age and gender’, *Energy and Buildings*. Elsevier B.V., 103(December), pp. 284–295. doi: 10.1016/j.enbuild.2015.05.042.

Karjalainen, S. (2013) ‘Should it be automatic or manual - The occupant’s perspective on the design of domestic control systems’, *Energy and Buildings*. Elsevier B.V., 65, pp. 119–126. doi: 10.1016/j.enbuild.2013.05.043.

Leaman A., S. F. B. B. (2010) ‘Building evaluation: Practice and principles’, *Building Research & Information*, 38(5), pp. 564–577. doi: 10.1080/09613218.2010.495217.

Nicol, F., Humphreys, M. and Roaf, S. (2012) *Adaptive thermal comfort. Principles and practice*. 1st edn. Abingdon: Routledge.

Nicol, J. F. and Humphreys, M. A. (2002) ‘Adaptive thermal comfort and sustainable thermal standards for buildings’, *Energy and Buildings*, 34(6), pp. 563–572. doi: 10.1016/S0378-7788(02)00006-3.

O’Brien, W. and Gunay, H. B. (2014) ‘The contextual factors contributing to occupants’ adaptive comfort behaviors in offices - A review and proposed modeling framework’, *Building and Environment*. Elsevier Ltd, 77, pp. 77–88. doi: 10.1016/j.buildenv.2014.03.024.

Schweiker, M. (2017) ‘Understanding Occupants’ Behaviour for Energy Efficiency in Buildings’. Current Sustainable/Renewable Energy Reports, pp. 8–14. doi: 10.1007/s40518-017-0065-5.

Schweiker, M. and Wagner, A. (2016) ‘The effect of occupancy on perceived control, neutral temperature, and behavioral patterns’, *Energy and Buildings*. Elsevier B.V., 117, pp. 246–259. doi: 10.1016/j.enbuild.2015.10.051.

Yan, D. *et al.* (2015) ‘Occupant behavior modeling for building performance simulation: Current state and future challenges’, *Energy and Buildings*. Elsevier B.V., 107, pp. 264–278. doi: 10.1016/j.enbuild.2015.08.032.

WORKSHOP 1

Usage and Interpretation of Comfort Scales

Invited Chairs:
Marcel Schweiker and
Giorgia Chinazzo

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

A field study investigation on the influence of light level on subjective thermal perception in different seasons

Giorgia Chinazzo[1], Luisa Pastore[1], Jan Wienold[1] and Marilyne Andersen[1]

[1] Laboratory of Integrated Performance in Design (LIPID), School of Architecture, Civil and Environmental Engineering (ENAC), École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland, giorgia.chinazzo@epfl.ch

Abstract: This paper evaluates the influence of light levels (i.e., illuminance) on subjective thermal perception of people, distinguishing between thermal sensation and thermal evaluation. The goal is to investigate whether reported effects found by other studies in controlled environments can be observed in real-life contexts and to understand if results are influenced by the season. By means of a post-occupancy evaluation conducted in four buildings in Switzerland, instantaneous air temperature and illuminance measurements were collected together with occupant's thermal perception votes during daytime in both summer and winter. Findings show that illuminance has a significant effect on the thermal perception of people, but only in terms of thermal evaluation and not of thermal sensation. In particular, results indicate that, at high temperature (above 25 °C), a less satisfying thermal evaluation is reported by people exposed to dim light (lower than 300 lux) compared to people exposed to brighter environments. We assume that this finding can be explained by *thermal expectations induced by light intensity*. The evaluation of data across summer and winter indicates that results are independent of the season (no interactions between illuminance, temperature and time of the year) and that the illuminance effect is accentuated depending on the season, which tends to highlight the psychological nature of thermal evaluation.

Keywords: thermal sensation, thermal evaluation, illuminance, seasonal effects, visual-thermal interactions.

1. Introduction

People experience the indoor environment as a whole, integrating stimuli from different perception areas such as thermal and visual (Parsons, 2014). For this reason, when one tries to understand how people perceive and react to a specific indoor factor, it is necessary to take into consideration some or all the other indoor factors (Bluyssen, 2013; Laurentin et al., 2000). As a consequence, in the thermal comfort research area, the parameters commonly considered to influence people's thermal perception (e.g., temperature, air speed, clothing, etc.) need to be integrated with other factors not directly linked to the thermal sphere such as light, sound and odour.

Conducting a holistic evaluation of the environment, i.e. that would take into consideration all the indoor factors, is a very difficult task (Rupp et al., 2015). But it is even more challenging to understand the interacting effects of specific factors on other spheres of perception. Very few studies have actually investigated the interactions amongst air quality, noise and thermal comfort (Fang et al., 1998; Huizenga et al., 2006; Levin, 1996; Tiller et al., 2010). The influence of light quantity on thermal responses has been analyzed in numerous experiments in controlled environments with a main focus on physiological reactions (e.g., core body temperature or skin temperature) and with light exposure in the evening or in the morning (te Kulve et al., 2015). On the other hand, very little is known on the effect of light on the subjective thermal perception of people and of this effect during day. In the context of this study, thermal perception is divided into two categories, i.e., thermal sensation and thermal evaluation. The sensation detects and describes a particular stimulus in the environments, whereas the evaluation is the conclusion of a process of reflection upon the sensation (Keeling et al., 2016). The results of existing studies on subjective thermal perceptions in controlled environments are contradictory, an outcome that might be caused by different durations and intensities of the light exposure but also by different timing of the experiment (te Kulve et al., 2016). By looking only at the experiments conducted during daytime (with the use of electric light), results appear more consistent, with subjects indicating to be cooler after the dim light exposure rather than under bright light exposure (Kim and Tokura, 2007, 1995, 2000; Teramoto et al., 1996).

Besides the lack of studies on subjective thermal perceptions, to our knowledge, no results are available for real environments from field studies, except a preliminary investigation of the authors, in which it was pointed out the necessity to investigate thermal conditions slightly outside of the comfort range (Chinazzo et al., 2016).

In addition, none of the studies analyses the influence of the time of the year, which indeed might affect results considering that seasons could change the light sensitivity and the prior light history of people (Hébert et al., 1998, 2002), besides the thermal adaptation according to the outside temperature (de Dear and Brager, 1998).

To address the aforementioned research gaps, the aim of this paper is to investigate visual-thermal interactions in terms of subjective evaluation in real contexts and in different seasons. More specifically, the goal is threefold: (i) examine whether the influence of light level (i.e., illuminance) on subjective thermal perception (in terms of thermal sensation and thermal evaluation) can be seen in real office environments, (ii) investigate if results are consistent with the ones reported in controlled studies and (iii) question whether the results are influenced by the season.

2. Method

A post-occupancy evaluation (POE) was conducted in four office buildings in Switzerland. To have a uniform sample, buildings were selected with comparable age of construction and energy-efficient strategies of design and operation. These buildings were all certified by the "Minergie" Swiss label, a certification system evaluating the annual energy use for heating, cooling, hot water and mechanical ventilation, requiring air-tight building envelopes and the use of energy-efficient ventilation system. The additional labels "P" and "Eco", present for two of the four buildings, indicate an increased attention to comfort criteria with respect to light, air quality and protection against noise. For example, Minergie-Eco provides further specifications about the minimum required contribution of daylight in the building. Other than that, the Minergie label does not give any additional insight on light compared to the Swiss norm (SIA, 2014). All buildings were equipped with HVAC systems but while two of them had completely air-tight facades, the other two were provided with openable elements that allow for natural ventilation.

The POE campaign was conducted over a series of days in both summer and winter in all four buildings. Measurements were conducted in the morning and in the afternoon, balancing the conditions in both seasons (in summer 50% in the morning and 50% in the afternoon; in winter 45% in the morning and 55% in the afternoon). Nevertheless, the "time of the day" variable was linked to the building analysed given the difficulty of changing location within the morning or the afternoon and the availability of participants in taking part to the survey in each building. As a result, the surveys were conducted in the morning in some buildings and in the afternoon in others. Considering that this variable will not be evaluated, in the following, all the data will be analysed independently of the building.

2.1. Objective of the field study

The conducted POE aimed at investigate visual-thermal interactions in different seasons. Based on a combination of objective (measured) data on temperature and illuminance, and on subjective (questionnaire-based) data on thermal perception of people in terms of thermal sensation and thermal evaluation, the objective was to determine whether subjective thermal perceptions changed according to illuminance levels. The same analysis was conducted in the two seasons to investigate seasonal variations.

2.2. Field study procedure

The POE consisted in point-in-time measurements of illuminance levels at the desk and at the eye level and of air temperatures together with questionnaires addressed to building occupants about their subjective thermal perception. More specifically, people were asked to report their *thermal sensation* (on a seven-point scale from cold to hot, according to the ASHRAE scale) and their *thermal evaluation* of the environment in terms of satisfaction with the temperature in the room (on a visual analogue scale with seven points, from very dissatisfied to very satisfied). The questionnaire was answered via an online form at the same time of the measurements. Participants were asked to report their evaluations in relation to the environment they were exposed to in the exact time of the survey and not to express their general feelings about the space they were daily working in.

The EPFL Ethical Committee approved the POE study protocol and all participants were first asked to read a written information sheet and to sign a consent form giving permission to measure the indoor environmental conditions in their offices, before filling in the questionnaires.

2.3. Participants

A total of 268 observations was collected across the two seasons, 108 in summer and 160 in winter. The mean age of participants (40.3 ± 12 in the total sample size) was equally distributed across seasons, with an average age of 39.7 ± 12 in summer and of 40.7 ± 12 in winter. The gender balance of participants was quite good across seasons, with 51 women and 57 men in summer and 77 women and 83 men in winter.

2.4. Recorded environmental conditions

Table 1 reports the environmental conditions measured in the POE in the two seasons.

It is interesting to notice that temperature means and distributions were very similar in the two seasons. Temperature values were generally higher than expected in winter, due to the presence of a mechanical control. This fact does not allow to investigate the effect of illuminance at lower temperature levels and will be further discussed in the next paragraphs.

Illuminance levels were a result of electric lighting and daylight. Lights in the spaces were typically on in both seasons (65% in summer and 66% in winter), meaning that at least one light in the measured rooms was on. Nevertheless, the contribution of daylight was significant, considering that the majority of subjects was working at less than 5 meters from the window (73% in summer and 72% in winter). The illuminance level from artificial light and its CCT were not recorded because the measurements had to be the least intrusive possible for the participants (i.e. not altering their work environment). In this study, we analyze only the desk illuminance, although the illuminance at the eye level was recorded as well.

Even though the measurements were planned to be taken under clear sky conditions, the sky was partially cloudy on one day in summer. Given the small variation of the sky conditions (i.e., not changing enough over the whole sample) and its correlation with season and the building analyzed, the effect of sky condition is not included in the analysis.

Table 1. Recorded indoor conditions in different seasons (mean ± standard deviation)

Indoor parameter	Summer	Winter
Desk illuminance [lux]	706 ± 659	883 ± 768
Eye level illuminance [lux]	540 ± 475	641 ± 488
Air temperature [°C]	24.2 ± 0.9	24.4 ± 1.3

2.5. Illuminance and temperature levels

For the analysis and the graphical representation of the results, subjective responses are plotted according to temperature and illuminance binned in three levels each. Temperatures are divided into "T ≤ 24", "24 < T < 25" and "T ≥ 25" (referring to °C), whereas illuminance levels into "E ≤ 300", "300 < E < 1000" and "E ≥ 1000" (referring to lux). These bins lead to comparable number of responses in both summer and winter (Table 2).

The illuminance values at the desk level are considered in the analysis. As the low illuminance threshold, 300 lux was chosen because it is at the same time the minimum value commonly considered for electric lighting in standards (SIA, 2006) and also the upper threshold considered in user assessment studies (performed in real situations) for manually switching on the artificial lighting (Reinhart and Voss, 2003). As the other illuminance threshold, 1000 lux was chosen because it is the upper threshold for the most light-demanding work (precision work), above which discomfort risks start to increase (Nabil Mardaljevic et al., 2006; Wienold, 2010).

Regarding temperature, the thresholds were chosen so as to have a comparable number of points in each bin and in each season. We are not describing the bins as "comfortable", "neutral" and "not comfortable" as the temperature thresholds should be different in summer and in winter, a fact that would make the analysis more difficult.

Table 2. Number of cases in each temperature and illuminance level, in both seasons

Illuminance [lux]	Summer	Winter
E ≤ 300	26	29
300 < E < 1000	61	82
E ≥ 1000	21	49

Temperature [°C]	Summer	Winter
T ≤ 24	54	64
24 < T < 25	33	51
T ≥ 25	21	45

2.6. Statistical analysis

To evaluate the influence of the different light levels on the thermal perception responses for each season, results are first displayed with a boxplot for each type of thermal perception response (i.e., thermal sensation and thermal evaluation). Then, to give further insights on the effect of light levels in each temperature bin, line graphs are used to display the mean positive/negative standard error of the mean (s.e.m.) for each temperature and illuminance combination in the two seasons (raw data are also plotted as dots of different shapes according to the illuminance level). Considering the type of data and the fact that they do not respect parametric assumptions, the non-parametric Kruskal-Wallis test is used for each season to assess whether the illuminance levels have an effect on the thermal perception responses. The associated effect sizes are calculated as well (Coolican, 2014). Whenever the Kruskal–Wallis test is significant, a post-hoc analysis is performed with the Dunn test to determine which levels of the independent variable differ from each other level. Zar (2013) states that the Dunn test is appropriate for groups with unequal numbers of observations, similar to our case. To control for the false discovery rate, the Benjamini & Hochberg adjustment to the p-values is used (Benjamini and Hochberg, 1995). A further Kruskal–Wallis test is used within each season and at each temperature level. Also in this case, post-hoc tests are applied to carry out all pairwise comparisons across illuminance levels within a specific temperature level. A three-way Analysis of Variance (ANOVA) is finally applied for each thermal perception response to verify the presence of interactions between illuminance, temperature and season. A significance level of $\alpha = 0.05$ is considered in the analysis, which is applied by the *R software.*

3. Results

The results are analyzed separately according to the two questions referring to the thermal perception – thermal sensation and thermal evaluation. In paragraph 3.1 we evaluate first the effects of illuminance on thermal sensation and then in 3.2 we investigate the effects of illuminance on thermal evaluation.

3.1. Illuminance effects on thermal sensation

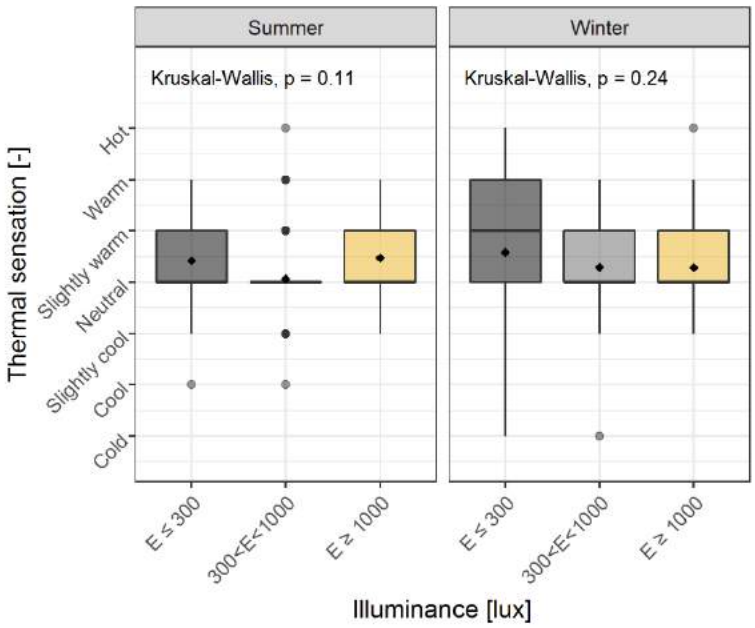


Figure 1. Thermal sensation responses according to the two seasons and the illuminance levels. Thick line: median; diamond: mean; circle: outlier.

Figure 1 shows the thermal sensation of users according to the three illuminance levels in both seasons. In the graph, the darker line indicates the median of the distribution, whereas the diamond represents the mean and the circles the outliers. Comparing both medians and means across illuminance levels, it appears that the thermal sensation of participants is not affected by the quantity of light, whether in summer or winter. This is confirmed by the Kruskal-Wallis test applied to results in the two seasons, which does not show any significant effect of illuminance on thermal sensation of people ($p > 0.05$). Figure 2 displays the same data but subdividing them into temperature levels. The means calculated from the resulting sample (too small in size, $n \leq 4$) are not displayed in the graph, but an extended dotted line is used to connect their values with the nearby displayed means (e.g., at $T \leq 24$ and for $E \leq 300$). The extrapolated lines thereby allow an appreciation of the thermal evaluation of subjects at all the temperature and illuminance combinations. By evaluating the graph, it appears that only temperature plays a role in the thermal sensation of people, while illuminance levels do not lead to differences - a consistent behaviour across the investigated temperature levels.

Interactions between temperature, illuminance and season are not present, as confirmed by the ANOVA test. As expected, the thermal sensation is affected only by temperature ($F = 22.7$, $p < 0.001$), with higher thermal sensation votes for higher temperatures in both seasons. Nevertheless, the Kruskal-Wallis test applied to each temperature level for each season, shows that in summer at T ≤ 24 the differences in thermal sensation votes for the illuminance levels are significant with χ^2 (2, n = 54) = 6.6, $p < 0.05$ (effect size $\eta^2 = 0.12$). The Dunn test reports a statistical significant difference only between “300 < E < 1000” and “E ≥ 1000” with a p-value adjusted of 0.04.

It appears therefore that in summer, at a lower temperature level, people exposed to higher illuminance feel warmer than people exposed to lower illuminance levels. Nevertheless, given the small effect size, this effect of illuminance on thermal sensation can be considered as negligible.

We can therefore conclude that the illuminance does not affect the thermal sensation of people neither in summer nor in winter.

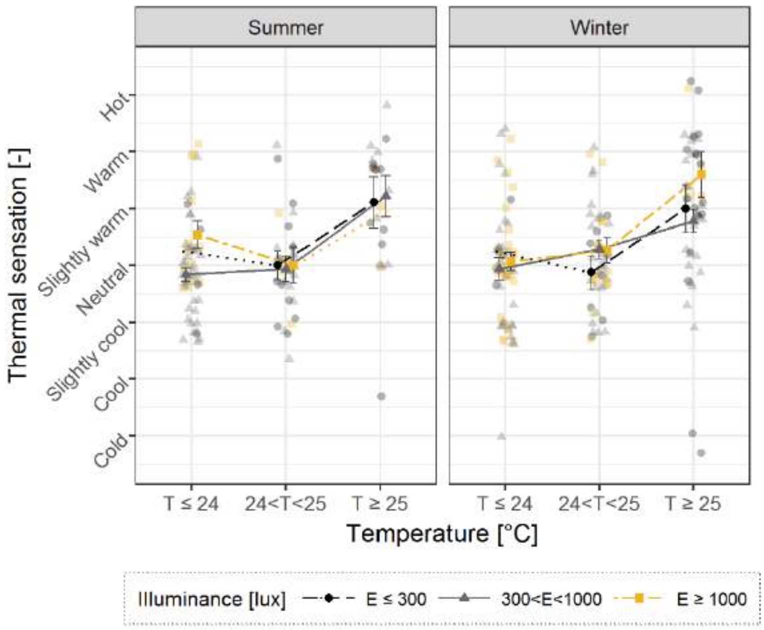


Figure 2. Thermal sensation response means ± s.e.m. according to the two seasons, temperature and illuminance levels.

3.2. Illuminance effects on thermal evaluation

Figure 3 displays the results for the thermal evaluation question in both summer and winter for all the illuminance levels. Looking at the means it appears clearly that thermal evaluation is affected by illuminance and that the thermal satisfaction is lower at lower illuminance levels. The Kruskal-Wallis test applied to data in both seasons, indicates illuminance as a significant factor in the determination of thermal evaluation with χ^2 (2, n = 108) = 11.6, $p < 0.01$ (effect size $\eta^2 = 0.10$) in summer and χ^2 (2, n = 160) = 13.0 $p < 0.01$ (effect size $\eta^2 = 0.08$) in winter. In both seasons, the post-hoc comparisons show that the differences between “E ≤ 300” and “300 < E < 1000” and between “E ≤ 300” and “E ≥ 1000” are significant, with a p-value adjusted of 0.027 and 0.002 in summer and of 0.001 and 0.002 in winter. The small effect can be explained by the fact that illuminance is not a statistically significant factor at each temperature level.

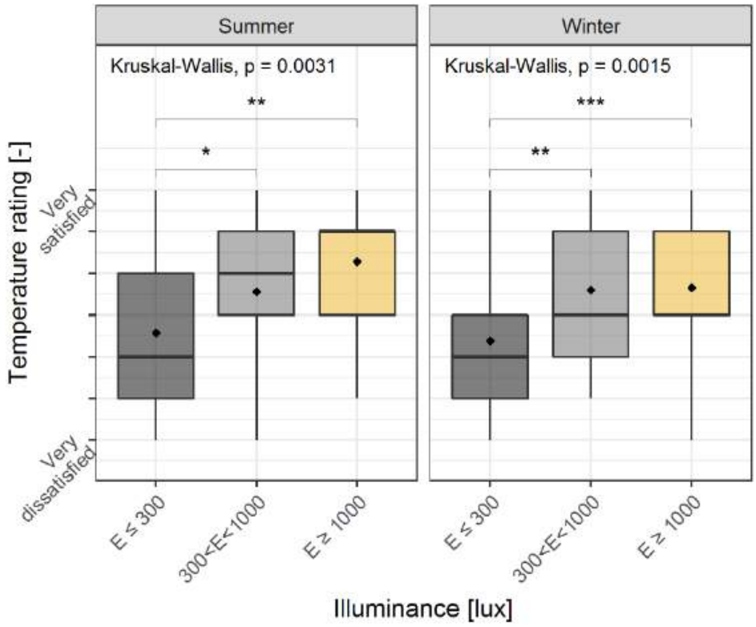


Figure 3. Thermal evaluation responses according to the two seasons and the illuminance levels. Thick line: median; diamond: mean; circle: outlier.

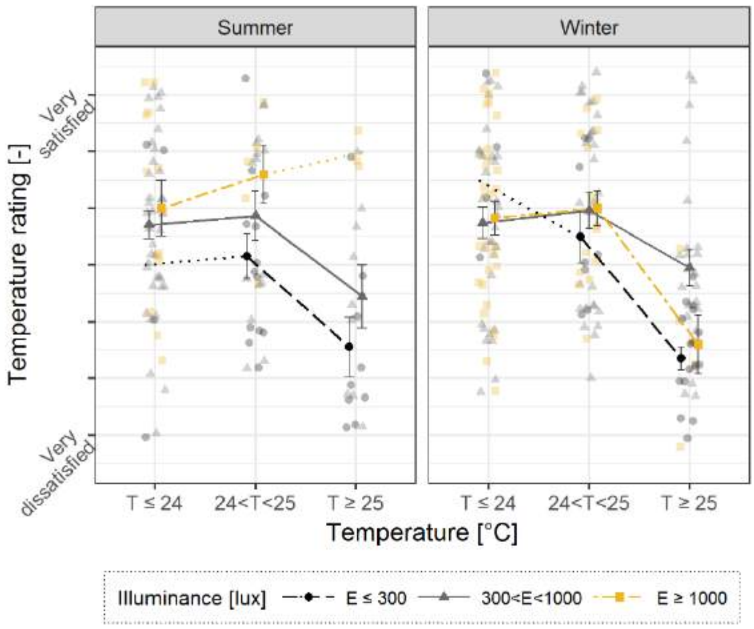


Figure 4. Thermal evaluation response means ± s.e.m. according to the two seasons, temperature and illuminance levels.

As can actually be seen in figure 4, even though the means for each temperature-illuminance combination appear quite different, the associated s.e.m. values are rather large, indicating a big spread of the data. The Kruskal-Wallis test conducted at each temperature level in each season investigates this problem. The results of the test indicate that the difference across illuminance levels is statistically significant only at "T ≥ 25" in both seasons, with χ^2 (2, n = 21) = 7.2, $p < 0.05$ in summer (effect size η^2 = 0.36) and χ^2 (2, n = 45) = 13.2, $p < 0.01$ in winter (effect size η^2 = 0.3). The Dunn test reports that in summer only between the illuminance levels "E ≤ 300" and "E ≥ 1000" there is a statistical difference with a p-value adjusted of 0.02, whereas in winter the difference is significant only between "E ≤ 300" and

“300 < E < 1000” with a p-value adjusted of 0.0012. No interactions between temperature, illuminance and season appear from the ANOVA analysis.

We conclude that illuminance is affecting thermal evaluation in both seasons, especially at higher temperature levels, resulting in lower temperature satisfaction under low illuminance levels.

4. Discussion

4.1. Illuminance effects on thermal perception

In this study, we found that illuminance has an influence on the thermal perception of the space in terms of thermal evaluation. On the other hand, no effect of illuminance has been found on the thermal sensation of people. Results from real office environments, therefore, are not consistent with the ones coming from laboratory experiments during daytime, where thermal sensation of people was shown to be influenced by illuminance, with participants feeling colder after the dim light exposure (Kim and Tokura, 2007, 1995, 2000; Teramoto et al., 1996). This discrepancy might result from the differences between the experimental and the field studies.

First of all, the experimental studies utilize electric light, whereas in real buildings the lighting environment is composed by both artificial light and daylight. Daylight might evoke other types of psychological effects compared to artificial light (e.g., direct sunlight in the room can be associated with a warmth sensation due to the related solar gains). Secondly, in field studies, many confounding factors that cannot be controlled can influence the thermal sensation of people, such as the clothing level or the presence of drafts. A small effect of illuminance on thermal sensation might therefore be behind these confounding factors. Finally, the procedures used and the stimuli involved in the two types of investigation are very different. The test room experiments investigate the effect of previous dim or bright light exposure (during daytime) on thermal sensation of people exposed to cold or decreasing temperatures in the following hours. All the authors report that the previous light exposure influences the core body temperature of people, reducing it under bright light compared to low light, a result that is confirmed in additional experiments (Aizawa and Tokura, 1997, 1998). As a consequence, they state that because of the higher set-point of core temperature after dim light exposure, the extreme change to low temperatures in the following hours leads to a bigger displacement from this internal state or *milieu interieur* according to the theory of *alliesthesia* (Cabanac, 1971; Dear, 2011), resulting in colder thermal sensations. In field studies, people are not exposed to such extreme “artificial” alterations of visual and thermal conditions, a fact that does not lead to changes in the *milieu interieur* and therefore does not affect their thermal sensation.

Nevertheless, the fact that we found a significant effect of illuminance on the thermal evaluation of the indoor environment confirms the substantial difference between *thermal sensation* and *thermal evaluation* (Keeling et al., 2016). In contrast with the *alliesthesia* that explains the relationship between sensation and evaluation with a physiological approach, Keeling et al. (2016) suggest that also psychological mechanisms lie behind the aforementioned relationship. Based on this conclusion and calling upon the adaptive comfort theory (de Dear and Brager, 1998; Nicol et al., 2012), we argue that the quantity of light can be one of the factors affecting people’s thermal evaluation of the environment.

Considering that participants under dim light were less satisfied with the temperature compared to people exposed to brighter light and that this effect was particularly significant at higher temperatures, we assume the *thermal expectation* induced by the quantity of light is affecting people’s thermal evaluation. In other words, if people are exposed to dim light they might expect the environment to be cooler (due to the lack of solar gains from sunrays) and whenever the temperature is still high, they are less satisfied with the thermal environment as it contradicts their thermal expectations. This assumption should be confirmed by other experiments.

4.2. Seasonal effects on interactions

We conducted the same type of analysis in both summer and winter to investigate whether the effect of illuminance on thermal perception is influenced by the time of the year. In particular, we wanted to see if interactions between illuminance, temperature and season were present, meaning that a particular effect of illuminance would have been present just in one season at a particular temperature level. Considering that findings are the same in both summer and winter, we argue that interactive effects between illuminance, temperature and season are not present.

On the other hand, the effect size of illuminance on thermal evaluation in summer is larger than the one in winter, supporting the hypothesis that the season is increasing the effect of illuminance on thermal expectation and therefore on thermal evaluation. As anticipated before, we did not record enough low temperatures in both seasons to investigate whether high illuminance at low temperatures would result in lower thermal evaluations. Consequently, it is also not possible to estimate whether this effect may be stronger in the winter compared to the summer.

4.3. Limitations of the study

Even tough field studies give a more realistic picture about the thermal perception of people in real contexts, they imply some limitations. The biggest constraint is that the conditions are not controllable but only measurable. We did not record very low temperatures in either seasons and, as a consequence, we did not test the effect of illuminance in cold thermal environments. Moreover, we did not have an equal distribution of subjects in each temperature-illuminance combination. We also did not have control on many other variables, such as the clothing of participants or the presence of other stimuli recognised to contribute to the thermal discomfort of people (such as draft, too low or cold surfaces, etc.). As light was found to be a combination of electric light and daylight, it is impossible to extract an effect of one of them separately. Moreover, it was not possible to acquire the previous light history of participants (e.g., if the light was on, when it was turned on and why). Finally, given the nature of the POE (i.e., measurements of buildings in different locations) some variables were related to the building itself, such as the time of the day and the sky conditions. These limitations could have an impact on the conclusions of this study and may in fact explain some of the inconsistencies found between the results and the ones of the climate chamber studies.

To address these issues and to be able to extrapolate results more widely, we foresee future experiments in a semi-controlled office environment (i.e., temperature is controlled while light is susceptible to changes due to season, time of the day and weather) to verify the findings of this study. The planned experiment will use only daylight as a source of light.

5. Conclusions

In this study, we investigate the effect of illuminance on thermal perception in real office environments in different seasons. To our knowledge, this is the first investigation about visual-thermal interactions evaluated in field studies and at different times of the year.

Our findings show that illuminance levels affect the thermal evaluation of the environment but not the thermal sensation of people, indicating a psychological effect rather than a physiological one. Results are therefore not consistent with the ones coming from laboratory studies, which report a physiological effect of light on thermal perception during daytime, with a consequent change in the thermal sensation of people. We hypothesize that this discrepancy can be explained by the substantial differences between experiments in a controlled environment and field studies.

By investigating the effect of illuminance on thermal evaluation at different temperature levels, we found that the effect was more significant at high temperatures (more than 25 °C) in both summer and winter, indicating that people exposed to dim light (less than 300 lux) were less satisfied about their thermal environment than people exposed to brighter light (higher than 300 lux) at the same temperature level. We assume that the quantity of light changes the *thermal expectations* of people resulting in lower thermal evaluation at high temperature under dim light compared to bright light, as people in a dim space would expect a cooler environment than the one they are actually exposed to.

By repeating the same procedure and analysis in both summer and winter, it was possible to study the seasonal effects of visual-thermal interactions. Findings show that the influence of illuminance on thermal perception is the same in both summer and winter, highlighting the fact that there are no interactions between season, temperature and illuminance. Nevertheless, we reported that the time of the year is influencing the results by accentuating the effect of illuminance on thermal evaluation. More precisely, we found that the effect of illuminance on thermal evaluation is larger in summer than in winter, as people exposed to dim light in a warm environment might expect to be cooler in summer compared to winter, leading to a larger thermal dissatisfaction with the environment in the warm season.

We believe that a similar analysis conducted in a more controlled environment would provide further insights on this topic. Also, the extension of this investigation to a bigger sample size with responses coming from other field studies, would greatly help the understanding of visual-thermal interaction in real contexts.

6. References

Aizawa, S. and Tokura, H., 1998. Influence of bright light exposure for several hours during the daytime on cutaneous vasodilatation and local sweating induced by an exercise heat load. *European journal of applied physiology and occupational physiology*, *78*(4), pp.303-307.

Aizawa, S. and Tokura, H., 1997. Exposure to bright light for several hours during the daytime lowers tympanic temperature. *International journal of biometeorology*, *41*(2), pp.90-93.

Benjamini, Y. and Hochberg, Y., 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the royal statistical society. Series B (Methodological)*, pp.289-300.

Bluyssen, P.M., 2009. *The Indoor Environment Handbook: How to make buildings healthy and comfortable*. Routledge.

Cabanac, M., 1971. Physiological role of pleasure. *Science*, *173*(4002), pp.1103-1107.

CEN, E., 2002. 12464-1: 2002 Light and lighting–Lighting of work places–Part 1: indoor work places. Bruss. Belg.

Chinazzo, G., Wienold, J. and Andersen, M., 2016. A preliminary study on the sensitivity of people to visual and thermal parameters in office environments. In *Proceedings of 9th Windsor Conference: Making Comfort Relevant*.

Coolican, H., 2014. *Research methods and statistics in psychology*. Psychology Press.

De Dear, R., 2011. Revisiting an old hypothesis of human thermal perception: alliesthesia. *Building Research & Information*, *39*(2), pp.108-117.

De Dear, R.J., Brager, G.S., Reardon, J. and Nicol, F., 1998. Developing an adaptive model of thermal comfort and preference/discussion. *ASHRAE transactions*, *104*, p.145.

Fang, L., Clausen, G. and Fanger, P.O., 1998. Impact of temperature and humidity on the perception of indoor air quality. *Indoor air*, *8*(2), pp.80-90.

Hébert, M., Dumont, M. and Paquet, J., 1998. Seasonal and diurnal patterns of human illumination under natural conditions. *Chronobiology international*, *15*(1), pp.59-70.

Hébert, M., Martin, S.K., Lee, C. and Eastman, C.I., 2002. The effects of prior light history on the suppression of melatonin by light in humans. *Journal of pineal research*, *33*(4), pp.198-203.
Huizenga, C., Abbaszadeh, S., Zagreus, L. and Arens, E.A., 2006. Air quality and thermal comfort in office buildings: results of a large indoor environmental quality survey. *Proceeding of Healthy Buildings 2006*, *3.*
Keeling, T.P., Roesch, E.B. and Clements-Croome, D., 2016. Cognitive appraisals affect both embodiment of thermal sensation and its mapping to thermal evaluation. *Frontiers in psychology*, *7*.
Kim, H.E. and Tokura, H., 2007. Influence of two different light intensities from 16: 00 to 20: 30 hours on evening dressing behavior in the cold. *Collegium antropologicum*, *31*(1), pp.145-151.
Kim, H.E. and Tokura, H., 1995. Influence of different light intensities during the daytime on evening dressing behavior in the cold. *Physiology & behavior*, *58*(4), pp.779-783.
Kim, H.E. and Tokura, H., 2000. Influence of light intensities on dressing behavior in elderly people. *Journal of physiological anthropology and applied human science*, *19*(1), pp.13-19.
Laurentin, C., Bermtto, V. and Fontoynont, M., 2000. Effect of thermal conditions and light source type on visual comfort appraisal. *International Journal of Lighting Research and Technology*, *32*(4), pp.223-233.
Levin, H., 1996. Design For Multiple Indoor Environmental Factors. In *Proceedings Indoor Air'96* (Vol. 2, No. 1, pp. 741-746).
Nabil, A. and Mardaljevic, J., 2006. Useful daylight illuminances: A replacement for daylight factors. *Energy and buildings*, *38*(7), pp.905-913.
Nicol, F., Humphreys, M. and Roaf, S., 2012. *Adaptive thermal comfort: principles and practice*. Routledge.
Parsons, K., 2014. *Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort, and performance*. CRC press.
Reinhart, C.F. and Voss, K., 2003. Monitoring manual control of electric lighting and blinds. *Lighting research & technology*, *35*(3), pp.243-258.
Rupp, R.F., Vásquez, N.G. and Lamberts, R., 2015. A review of human thermal comfort in the built environment. *Energy and Buildings*, *105*, pp.178-205.
SIA, 2006. SIA 380/4 L'énergie électrique dans le bâtiment.
te Kulve, M., Schellen, L., Schlangen, L., Frijns, A.J.H. and van Marken Lichtenbelt, W.D., 2016. Light intensity and thermal responses. In *Making Comfort Relevant: Proceedings of 9th Windsor Conference* (pp. 1-8).
te Kulve, M., Schellen, L., Schlangen, L.J.M. and Marken Lichtenbelt, W.D., 2016. The influence of light on thermal responses. *Acta Physiologica*, *216*(2), pp.163-185.
Teramoto, Y., Tokura, H., Ohkura, K., Ohmasa, Y., Suho, S., Inoshiri, R. and Masuda, M., 1996. Effects of different light intensities during the forenoon on the afternoon thermal sensation in mild cold. *Journal of thermal biology*, *21*(5-6), pp.339-343.
Tiller, D.K., Wang, L.M., Musser, A. and Radik, M.J., 2010. Combined effects of noise and temperature on human comfort and performance. In *2010 ASHRAE Annual Conference*.
Wienold, J., 2010. *Daylight glare in offices*. Fraunhofer-Verlag.
Zar, J.H., 2013. *Biostatistical Analysis: Pearson New International Edition*. Pearson Higher Ed.

Collective understanding of ASHRAE thermal sensation phrases among Arab students

Hanan Al-Khatri[1,2] and Mohamed B. Gadi[1]

[1] Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, UK, Hanan.Al-Khatri@nottingham.ac.uk;
[2] Department of Civil and Architectural Engineering, College of Engineering, Sultan Qaboos University, Oman, khatri@squ.edu.om

Abstract: Despite their widely spread application, thermal scales' behaviour is not always well understood, especially between non-native English subjects. Examining some translations implemented in recent Arabic studies revealed differences from the international Arabic version. This version, itself, is questioned as its formation and the dialect it considers are not obvious. Moreover, positive impressions were possibly associated with phrases outside the widely accepted range of comfort in the investigated translations. In this regard, two short questionnaires were distributed among Omani high school students to explore their collective understanding of ASHRAE thermal sensation phrases. In the first, the students were requested to translate the phrases into Arabic, order them, and identify (thermal comfort). The second was a multiple-choice questionnaire which questions were derived from the answers of the first. Analysing results revealed a variety in the translated phrases that ranged from 7 to 44, which may be related to the Arabic language features. Besides, there was a weak agreement between the students' translations and the internationally accepted version. Phrases like (slightly cool) and (slightly warm) were not clear for most students. Further research is recommended to explore the impact of using phrases like (cool and not acceptable) and (warm and not acceptable).

Keywords: Thermal scale, Translation, Arabic language, Students, Oman

1. Introduction

1.1. Thermal sensation scales

Sensitivity to thermal conditions is known as thermal sensation and it is widely considered as a determination of subjects' thermal comfort (Givoni, et al., 2003). As a psychological experience, thermal sensation is related to peoples' feelings about ambience (Parsons, 2014) and it is affected by thermal experience and expectation (Hoppe, 2002). Subjects' thermal sensation is widely assessed by thermal scales that are recommended to adopt the local context. This is achieved by considering participants' social, cultural, and economical characteristics besides translating scales to the local languages (Mishra & Ramgopal, 2013; Singh, et al., 2011). Several sensation scales are found in literature (Schweiker, et al., 2017; Lee, et al., 2010), among which ASHRAE verbal scale is widely used.

1.2. Translating thermal comfort phrases

Ideally, translation should reflect the original text meaning and impression. However, this is not always achievable because some thermal phrases have different impressions or no equivalents in other languages. Therefore, priority in translating thermal scales is to ensure identical chances of sensations selection (Humphreys, 2008) possibly through considering the climatic background influence.

Considering the international nature of thermal comfort studies, the translation effect should not be underestimated. Yet, few studies investigated this effect. In SCATs (Smart Controls and Thermal Comfort) project, ASHRAE sensation scale was translated to French, Swedish, Greek, and Portuguese languages and then to English to explore any variations in translated phrases (Humphreys, 2008). In another study, Arab, Chinese, and Greek subjects among others were requested to translate the phrases of ASHRAE thermal sensation scale into their native languages, distribute them on a line considering their intermediate gaps and order, and indicate (comfort) on the same line (Pitts, 2006). Interestingly, both studies confirmed translated phrases divergence from their English equivalents.

1.3. Challenges in translating thermal phrases into Arabic

An international translation of ASHRAE scale to Arabic language is available (Parsons, 2014). However, the methodology of formulating this translation is not clear nor the dialect it considers. In Table 1, the international version is compared with other translations used in recent studies. As noted, the agreement with the international version was in two phrases for all the translations except (Shohan, 2015) and (Sufeljen, 2014) as they agreed in three and one phrases respectively. It should be mentioned that two Arabic terms were provided for (warm) and (hot) in (Shohan, 2015), whereas (slightly warm) and (warm) translations were exchanged in (Sufeljen, 2014). Noteworthy to mention that the head question of these studies, except (Sufeljen, 2014), requested subjects to evaluate their ambience or thermal comfort.

Table 1. Different Arabic translations of ASHRAE thermal sensation phrases

ASHRAE phrases	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
International version	شديد البرودة	بارد	خفيف البرودة	طبيعي	خفيف الحرارة	حار	شديد الحرارة
(Alwetaishi, 2015)	بارد جدا	بارد	بارد بعض الشيء	مرتاح	دافئ	حار	حار جدا
(Shohan, 2015)	شديدة البرودة	باردة	مائلة للبرودة قليلا	مريحة	مائلة للدفء قليلا	ساخنة أو حارة	ساخنة أو حارة جدا
(Sufeljen, 2014)	بارد جدا	بارد	بارد قليلا	معتدل	ساخن	ساخن قليلا	ساخن جدا
(Saleh, 2011)	بارد جدا	بارد	بارد قليلا	مريح	حار قليلا	حار	حار جدا
(Farghal & Wagner, 2010)	بارد جدا	بارد	بارد بعض الشيء	معتدلة	حار بعض الشيء	حار	حار جدا

Additionally, all translations in Table 1, including the international version, used the Arabic meaning of (hot) as an equivalent to (warm) and, consequently, replaced (hot) by (very hot). The reason may be to convey a negative impression as the Arabic meaning of (warm) can be considered as a desirable sensation, especially in winter. In other words, maintaining the literal translation of (warm) may lead to a positive impression outside the widely accepted range of comfort (i.e. slightly cool to slightly warm). In this regard, it is noted that the Arabic literal translation of (warm) was used as equivalent to (slightly warm) sensation in (Alwetaishi, 2015).

Considering the cold side, the range between (cold) and (cool) is usually described by one phrase possibly reflecting the influence of warm climatic conditions dominant in the Arabic region. Consequently, (cold) was replaced by (very cold) in Table 1 translations. In addition, the currently used phrase for (cool) is often a desirable sensation in most Arabic countries, including Oman, especially in summer. Obviously, these translations do not convey the impressions of the original English phrases outside the comfort range. Yet, it should be highlighted that this range is assumed and, therefore, further investigations are recommended (Humphreys, et al., 2016), particularly in the Arabic region. Similar manipulation was applied to the warm side phrases in French, Greek, and Portuguese languages in SCATs project (Humphreys, 2008).

Furthermore, ASHRAE scale in its seventh categories form is mainly applicable in thermally moderate environments. For extreme conditions, (very cold) and (very hot) categories are added to the scale (Humphreys, et al., 2016). Hence, considering Table 1 translations as equivalent to the English phrases of ASHRAE scale may be doubtful, despite their attempts to convey similar impressions.

2. Methodology

The study reported in this paper is an attempt to explore the collective understanding of ASHRAE scale phrases among eastern Arabs, with reference to Oman. Particularly, it aims to identify the Arabic phrases equivalents to ASHRAE scale phrases and their distribution on the thermal continuum. Besides, it explores thermal comfort for the involved participants.

2.1. Data

In this study, two questionnaires were distributed over a year as depicted in Figure 1. The first questionnaire was distributed in the first and second visits and it was similar to that designed by (Pitts, 2006). Students were requested to translate thermal sensation phrases of ASHRAE scale to Arabic, order them on a linear scale that resembles the thermal continuum, and identify thermal comfort. In order to assist students, they were asked if it is possible to consider any of ASHRAE sensation phrases as an equivalent to thermal comfort. If their answer was (yes), they were asked to specify that phrase. Oppositely, if their answer was (no), they were asked to determine the thermal comfort on the given linear scale.

Moreover, the translated phrases provided by 5% of students or more were used to construct the second questionnaire. This multiple-choice questionnaire was distributed in the second and third visits. Students were asked to choose the most accurate Arabic phrase for each thermal sensation and were encouraged to provide new phrases if they felt the need to. It should be mentioned that questions' order was different from that of ASHRAE scale.

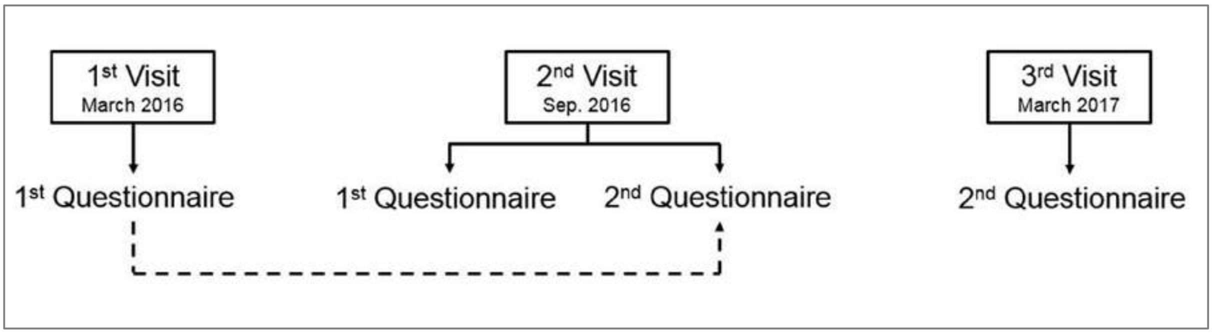


Figure 1. Sequence of questionnaires' distribution

In addition, a general introductory lecture about thermal comfort was delivered in the second visit to familiarise students with the research aiming to increase participation rate. Initially, it was not planned to deliver such lecture to avoid influencing students' answers. Yet, distributing the first questionnaire revealed their lack of confidence in answering the questions possibly because this study was the first participation in a scientific research for almost all of them.

2.2. Subjects and Arabic language

Participants were female students from five high schools in Muscat city. The students were between 15 and 18 years old and they studied English as a second language for, at least, 9 years. The native tongue of the students is Arabic. Arabic language is spoken in a wide geographical area that extends from Oman to Morocco. Linguists differentiate between two levels of Arabic, namely Classical Literary Arabic and Modern Standard Arabic. In addition, several dialects of Arabic language are distributed in different geographical regions. Their variations increase as distances increase, which may form a barrier against understanding between people from different regions. In such cases, people tend to speak Modern Standard Arabic that is understood by all Arabs although used vocabulary differs according to the speaker's region (Holes, 2004).

2.3. Climatic conditions

The schools are located in Muscat, the capital city of Sultanate of Oman. Muscat is within a desert hot arid climate based on Koppen-Geiger climate classification. However, its proximity from the Indian Ocean and its mountainous nature changed its climate to a hot humid (Al-Azri, et al., 2012; Ragette, 2012; Konya & Vandenberg, 2011). In general, the year is divided into two climatically distinctive periods. The hot humid period, extending between April and October, is characterised by 30-35 °C mean air temperature and 42%-74% mean relative humidity. The other months form the cooler period that has mean air temperature extending between 21 °C and 26 °C and mean relative humidity ranging from 57% to 66%.

3. Results and discussion

In total, 762 copies of the first questionnaire and 612 copies of the second were distributed. Around 68% of the first questionnaire copies were excluded due to missing and inconsistent answers. Wrong translations such as calm, clean, and dangerous resulted in excluding the entire copy. In addition, other copies that translated cool as warm or warm as cold were excluded. Accordingly, 245 copies of the first questionnaire were analysed. However, the polarity of the second question scale was inverted in 13 copies. This was corrected as part of preparing the results for analysis. Further, the scale's length was converted to a 100 mm. In the second questionnaire, the response rate was 100%.

3.1. Translations of ASHRAE scale phrases

(Cold) and (hot) were translated into 13 and 14 different terms respectively, which means that on average almost 19% and 18% of students agreed on one phrase for the former and the latter sensations. The highest number of translated phrases was 109 for (slightly cool), followed by 91, 64, 39, and 36 for (slightly warm), (cool), (neutral), and (warm) respectively. The authors, who are native speakers of Arabic, merged similar translated phrases of each sensation. Consequently, the respective translated phrases of (cold), (cool), (slightly cool), (neutral), (slightly warm), (warm), and (hot) became 7, 25, 44, 20, 42, 20, and 7. The variation in translated phrases used for each sensation may be related to the nature of the Arabic language. Often, there are many Arabic words to describe the one thing. For example, more than 100 Arabic words were used to describe (pain) resulted from a study performed in Kuwait (Harrison, 1988). Likewise, there are around 11 different words that mean (love) in Arabic language (Sayed, 2015). Reflecting this into the research at hand, it is possible, for instance, to identify four and two different words used as translations for (neutral) and (hot) respectively in the merged version. Besides, Arabic roots words can create tens of words (Awajan, 2015), which allowed the students to create different translations for the one sensation using one root word like the cases of (cold) and (cool).

Additionally, it was noted that most students translated the sensations into phrases of two words, which added to the variety of their answers considerably. Moreover, it should be mentioned that merging similar translations was possible due to the flexible order of Arabic words (Saiegh-Haddad, 2017; Awajan, 2015).

Moreover, the unmerged translated phrases provided by 5% of students or more are depicted in Figure 2. Any phrases provided by less than 5% were added to (other). As noted, more than 50% of students agreed on one phrase for each of (cold), (neutral), (warm) and (hot). Yet, they did not agree on specific phrases for the remaining sensations. Possible reasons include their level of knowledge as they, frequently, asked about the meaning of (slightly) besides the warm conditions dominant in Muscat city.

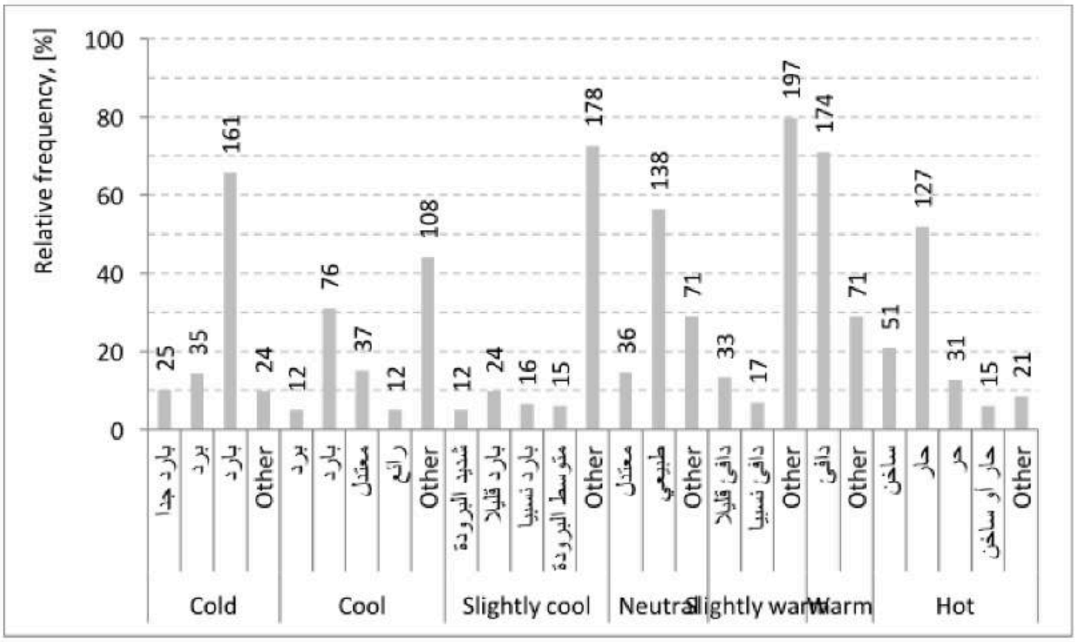


Figure 2. Relative frequency of unmerged translated phrases (Labels are students' numbers)

Besides, it is noted in Figure 2 that some translated phrases were common between sensations. This may reflect a possible overlap in sensations' meanings for the investigated students. Overall, (cool) and (slightly cool) had the highest number of common phrases as they shared 18 terms followed by (slightly warm) and (warm) that shared 11 phrases. Besides, 10 phrases were common between (cool) and (neutral) and between (neutral) and (warm). It is noteworthy to mention that most of these phrases were provided by less than 5% of students. Indeed, only three common phrases from the unmerged translations were provided by 5% of students or more. These are:

- (**برد**) used for (cold) and (cool) by 14% and 5% respectively,
- (**بارد**) used for (cold) and (cool) by 66% and 31% respectively, and
- (**معتدل**) used for (cool) and (neutral) by 15% and 15% respectively.

The relatively high agreement on the common phrases between (cold) and (cool) may reflect the general lack of differentiation between them in Arabic language. In this regard, a similar lack was noticed for (warm) and (hot) in French, Greek, and Portuguese languages in the SCATs project (Humphreys, 2008).

Considering merged translations, the common phrases provided by 5% of students or more are depicted in Figure 3. Based on the percentages, it may be possible to assign a common phrase to a certain sensation. For instance, (slightly warm) and (warm) were translated into one phrase by 6% and 72% of students respectively. Thus, it may be possible to consider that common phrase as equivalent to (warm). Moreover, a phrase that literally means (moderate), (mild), or (neither cool nor warm) was repeatedly used to express thermal sensations between (cool) and (warm) including both. Interestingly, the number of students who translated (cool) as (moderate) was slightly higher than those used it as an equivalent for (neutral). In general, this overlapping may be significant in the cases of (cool) and (slightly cool), (cool) and (neutral), and (slightly cool) and (neutral) as their percentages were relatively similar. Besides, the repetitive use of this phrase may indicate a wide acceptance of thermal conditions among the investigated students.

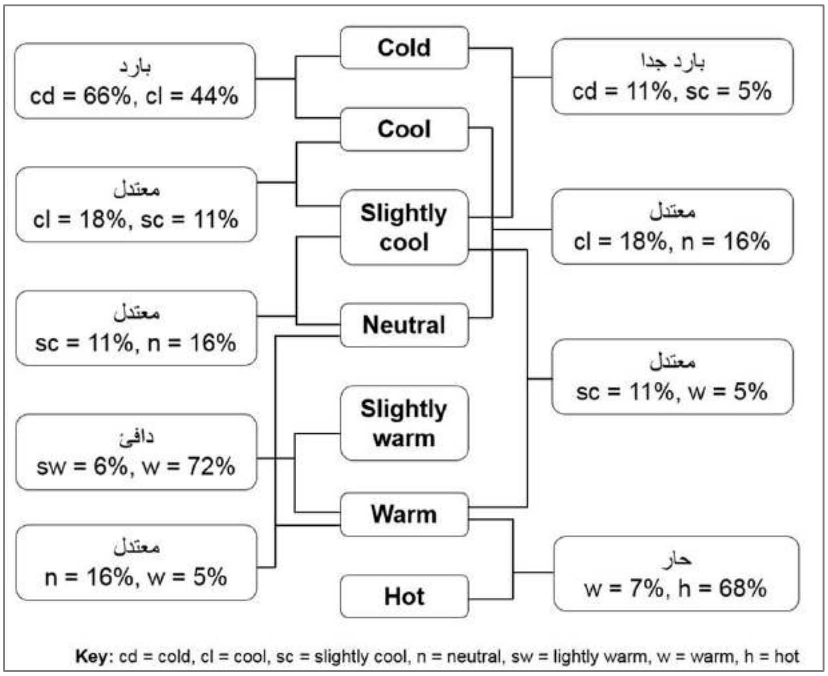


Figure 3. Common phrases between merged translated phrases

For each sensation, the phrases provided by the highest number of students before and after merging are displayed in Table 2 besides the second questionnaire findings. Merging similar phrases resulted in using one phrase as an equivalent for both (cold) and (cool), which may reflect their cover of the same thermal range. Moreover, the agreement percentages increased slightly except for (hot) that increased by 16.4% approximately. It seems that many different phrases were provided as equivalent to (hot) possibly due to the dominant climatic conditions in Muscat city. Besides, the students' confusion about (slightly) meaning is obvious as even merging did not result in identifying one translated phrase for both (slightly cool) and (slightly warm). However, they agreed on equivalents for these sensations in the second questionnaire though the agreement percentages were lower than other sensations. In addition, (cool) equivalent in the second questionnaire was different from that resulted from merging. Based on the second questionnaire, (cool) was translated as (moderate), (mild), or (neither cool nor warm). This suggests the importance of considering climatic background influence when defining the comfort range.

It is noted that students' translations summarised in Table 2 differ from those of the international version presented in Table 1 except (cool), from the merged version, and (neutral). Recalling that the considered dialect in the international translation is not known, variations may be justified because dialects affect the used vocabulary. This highlights the importance of considering participants' local context through careful translations of thermal scales.

Table 2. Thermal sensations' equivalents before merging, after merging, and from the second questionnaire

Thermal sensation	Cold (%)	Cool (%)	Slightly cool (%)	Neutral (%)	Slightly warm (%)	Warm (%)	Hot (%)
Before merging	بارد (65.7)	**Other (44.1)**	**Other (72.7)**	طبيعي (56.3)	**Other (79.8)**	دافئ (71.0)	حار (51.8)
After merging	بارد (66.1)	بارد (4.7)	**Other (46.9)**	طبيعي (59.2)	**Other (60.4)**	دافئ (71.8)	حار (68.2)
2nd questionnaire	بارد (82.4)	معتدل (44.9)	متوسط البرودة (36.9)	طبيعي (86.9)	دافئ قليلا (57.8)	دافئ (84.8)	حار (73.2)

3.2. Comparing categories means

Mean, median, range, and standard deviation values were calculated for each sensation besides thermal comfort as presented in Table 3. As observed, the range of each sensation almost extended over the 100 mm line, which may reflect students' uncertainty regarding sensations' positions along the thermal continuum. Besides, it seems that distinguishing between (cool) and (slightly cool) was difficult as their means and standard deviations were similar, which was also the case with (slightly warm) and (warm). For the last two sensations, the mode values were identical. It may worth mentioning that the mode was determined by around 7% and 5% of students for the former and latter sensations respectively. Additionally, (neutral) mean was marginally shifted from the centre towards the hot side, whereas (comfort) mean was slightly shifted towards the cold side. Indeed, (comfort) shift is consistent with the general preference tendency of people from warm climates (Humphreys, et al., 2016; Nicol, et al., 2012; de Dear & Brager, 1998). The standard deviation of (comfort) was noticeably higher than that of (neutral), which may indicate wider comfortable ranges.

Table 3. Statistics of thermal sensations (N = 245)

	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Comfort
Mean	**20.16**	**32.89**	**34.84**	**51.23**	**64.14**	**66.71**	**79.73**	**46.53**
Median	**14**	**29**	**34**	**52**	**65**	**70**	**87**	**49**
Mode	**13**	**23**	**34**	**52**	**74**	**74**	**86**	**53**
SD	**20.02**	**18.15**	**16.24**	**10.98**	**16.48**	**17.53**	**21.84**	**17.49**
Max.	**103**	**91**	**93**	**102**	**100**	**99**	**102**	**93**
Min.	**0**	**0**	**0**	**14**	**11**	**12**	**3**	**0**
Range	**103**	**91**	**93**	**88**	**89**	**87**	**99**	**93**

Furthermore, possible equivalence between thermal sensations in this sample was explored through computing confidence intervals of sensations' means. A 0.01 level of significance was selected to allow for the possible widest intervals. Results are presented in Figure 4. Regardless of their close proximity, students distinguished between (comfort) and (neutral). Moreover, almost 75% of (slightly cool) interval overlapped with that of (cool) and around 50% of (slightly warm) interval overlapped with (warm) interval. This may be due to students' uncertainty about the meaning of (slightly).

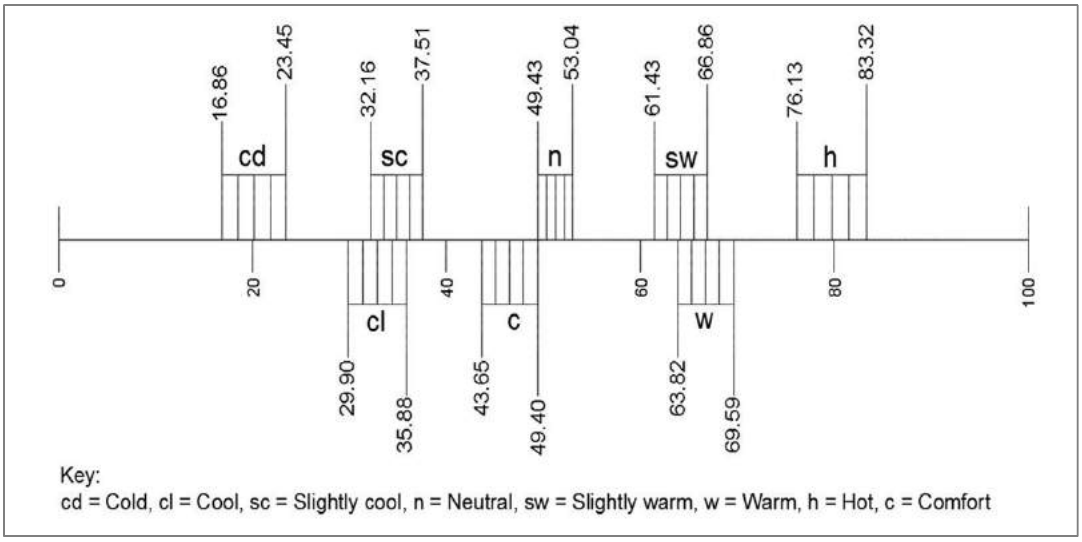


Figure 4. Distribution of means' 99% confidence intervals (N = 245)

Categories means based on sensations order

For further examination, data were classified into two sets based on the sensations order in the second question of the first questionnaire. ASHRAE order was followed in the first set, whereas other orders were found in the second set. Some statistics are displayed in Table 4 for the former and in Table 5 for the latter. As expected, the ranges of the first set were considerably narrower and the means had a relatively uniform distribution on the thermal continuum. In the second set, means of (slightly cool) and (warm) were lower than those of (cool) and (slightly warm) respectively. In both sets, (neutral) mean was marginally above the centre and (comfort) mean was slightly below.

Table 4. First set statistics – ASHRAE order (N = 81)

	Cold	**Cool**	**Slightly cool**	**Neutral**	**Slightly warm**	**Warm**	**Hot**	**Comfort**
Mean	**12.53**	**24.15**	**35.49**	**50.88**	**63.83**	**75.78**	**86.56**	**46.48**
Median	**13**	**23**	**35**	**52**	**64**	**77**	**87**	**49**
Mode	**12**	**23**	**34**	**53**	**64**	**80**	**86**	**53**
SD	**6.47**	**5.98**	**6.24**	**5.62**	**8.51**	**9.19**	**9.59**	**14.85**
Max.	**29**	**38**	**46**	**65**	**80**	**95**	**102**	**83**
Min.	**0**	**10**	**21**	**29**	**34**	**40**	**45**	**11**
Range	**29**	**28**	**25**	**36**	**46**	**55**	**57**	**72**
99% Conf. intr.	**10.68 – 14.38**	**22.44 – 25.86**	**33.71 – 37.28**	**49.27 – 52.48**	**61.39 – 66.26**	**73.15 – 78.41**	**83.81 – 89.30**	**42.23 – 50.73**

Moreover, the means of these two sets are graphically compared with those of the total set as plotted in Figure 5. Means of (comfort) and central categories sensations were almost similar in the three sets. Compared with the first set, both (cold) and (cool) were warmer in the total and second sets. Likewise, (warm) and (hot) were cooler in the second and total sets. The influence of sample size was obvious as the means of the second and total sets had similar positions.

Table 5. Second set statistics – another order (N = 164)

	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Comfort
Mean	**23.93**	**37.21**	**34.51**	**51.41**	**64.30**	**62.23**	**76.35**	**46.55**
Median	**15**	**35**	**32**	**52**	**67**	**65**	**87**	**49**
Mode	**13**	**41**	**35**	**52**	**74**	**63**	**90**	**47**
SD	**23.16**	**20.46**	**19.38**	**12.84**	**19.26**	**18.91**	**25.18**	**18.70**
Max.	**103**	**91**	**93**	**102**	**100**	**99**	**100**	**93**
Min.	**0**	**0**	**0**	**14**	**11**	**12**	**3**	**0**
Range	**103**	**91**	**93**	**88**	**89**	**87**	**97**	**93**
99% Conf. intr.	**19.27 – 28.59**	**33.09 – 41.32**	30.61 – **38.41**	**48.83 – 53.99**	60.42 – **68.17**	**58.42 – 66.03**	**71.29 – 81.42**	**42.77 – 50.31**

Figure 5. Means of thermal sensations in the first, second, and total sets

Additionally, the 99% confidence intervals of the first and second sets means are depicted in Figure 6. In the former, students distinguished between sensations as means distributed without any overlap. Considering the second set, around 68% of (slightly cool) interval overlapped with that of (cool). Similarly, almost 72% of (slightly warm) interval overlapped with (warm) interval. It seems that most students who were confused about (slightly) meaning belonged to this set. Thus, it may be concluded that the overlapping in the total set intervals was exclusively due to the overlapping in the second set.

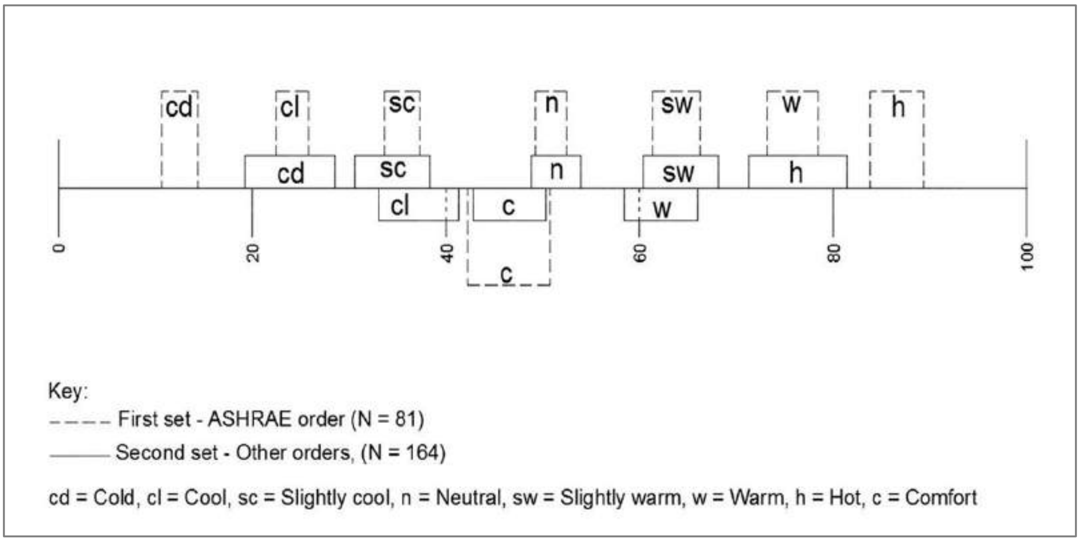


Figure 6. Distribution of means' 99% confidence intervals in the first and second sets

Categories means based on season

Students' answers of the second question in the first questionnaire were divided into summer and winter sets to explore possible seasonal impact. Table 6 presents some basic statistics of the former set that consisted of 163 copies. The remaining copies formed the winter set which statistics are displayed in Table 7. As noted, ranges are relatively narrower in winter as all sensations' means fell within the given scale. Oppositely, (cold), (neutral), and (hot) in summer exceeded the scale, which was reflected in the relatively wider standard deviations. Although means in both sets followed ASHRAE order, the relative distances between them were not uniform. Moreover, it is noted that (cool) and (slightly cool) were closer than other sensations in both sets, which was the case with (slightly warm) and (warm) in summer set only. Considering (comfort), it was cooler than (neutral) in both sets, which is, as mentioned earlier, consistent with the general preference of people from warm climates (Humphreys, et al., 2016; Nicol, et al., 2012; de Dear & Brager, 1998). It is worth to mention that the difference between (comfort) and (neutral) was relatively higher in summer, which may indicate the seasonal impact on determining the former for the investigated students.

Furthermore, the means are graphically represented in Figure 7 that, additionally, displays means of (Pitts, 2006). Compared with summer, the cool side means in winter were negligibly cooler and those of the warm side were slightly warmer. Considering each set separately, the relatively bigger differences between warm side means possibly indicate wider acceptance of warm conditions. On the other hand, the relatively smaller variations between cool side means may reflect higher sensitivity towards cool conditions. In addition, (cold) and (cool) means in Pitts' set were noticeably cooler than their equivalents for Omani students, which may be due to the participants' thermal experiences. However, (warm) and (hot) means were surprisingly hotter in Pitts' data. The reason may be cultural considering the spread of air conditioners in Omani buildings (Al-Gharibi, 2016; Abdul-Majid, et al., 2014).

Table 6. First set statistics – summer (N = 163)

	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Comfort
Mean	**20.72**	**33.94**	**35.30**	**50.55**	**63.34**	**64.75**	**77.44**	**43.98**
Median	**12**	**27**	**34**	**52**	**66**	**68**	**87**	**47**
Mode	**11**	**23**	**34**	**50**	**68**	**71**	**86**	**53**
SD	**23.39**	**20.74**	**18.66**	**12.19**	**18.95**	**19.43**	**26.09**	**19.52**
Max.	**103**	**91**	**93**	**102**	**100**	**99**	**102**	**93**
Min.	**0**	**0**	**0**	**14**	**11**	**13**	**3**	**0**
Range	**103**	**91**	**93**	**88**	**89**	**86**	**99**	**93**
99% Conf. intr.	**14.07 – 27.38**	**28.05 – 39.84**	29.99 – **40.61**	**47.08 – 54.02**	57.95 – **68.73**	**59.22 – 70.27**	**70.02 – 84.86**	**38.43 – 49.53**

Table 7. Second set statistics – winter (N = 82)

	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Comfort
Mean	**19.04**	**30.79**	**33.91**	**52.59**	**65.73**	**70.60**	**84.27**	**51.94**
Median	**15**	**29**	**34**	**52**	**65**	**73**	**86**	**52**
Mode	**13**	**21**	**34**	**51**	**64**	**79**	**87**	**53**
SD	**10.54**	**11.20**	**9.86**	**7.93**	**9.82**	**12.18**	**6.65**	**10.93**
Max.	**71**	**73**	**74**	**85**	**84**	**89**	**97**	**78**
Min.	**4**	**12**	**16**	**30**	**21**	**12**	**61**	**21**
Range	**67**	**61**	**58**	**55**	**63**	**77**	**36**	**57**
99% Conf. intr.	**16.04 – 22.04**	**27.61 – 33.98**	31.11 – **36.72**	**50.33 – 54.84**	62.94 – **68.52**	**67.13 – 74.06**	**82.38 – 86.16**	**48.83 – 55.05**

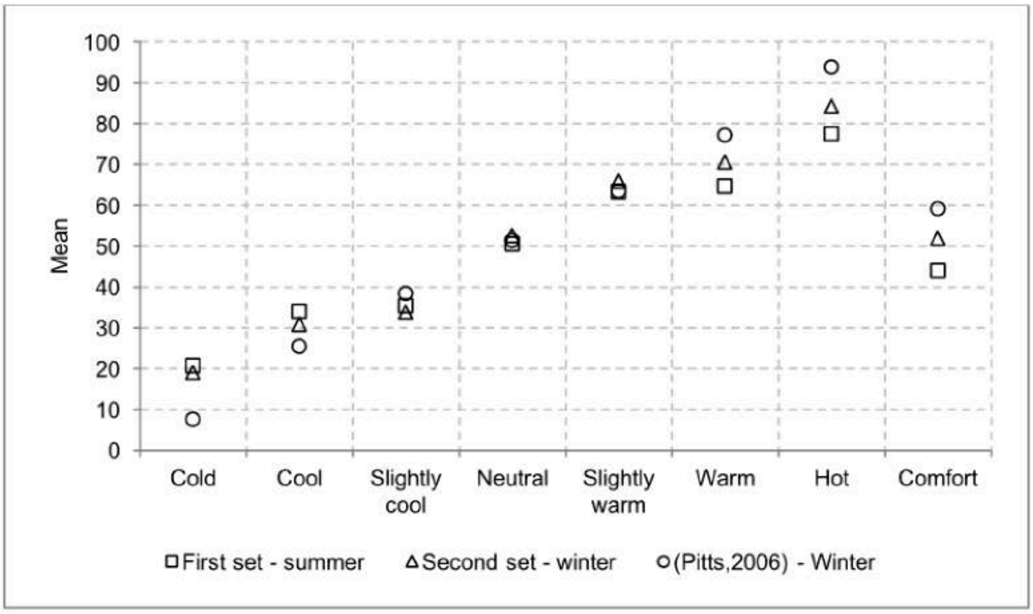


Figure 7. Means of thermal sensations in the first, second, and Pitts' sets

Furthermore, Figure 8 presents the 99% confidence interval of both summer and winter sets. Despite its larger size, wider intervals were noted in the former set possibly due to its considerable variability indicated by the relatively wider standard deviations. Besides, around 93% of (slightly cool) interval overlapped with that of (cool) and almost 88% of (slightly warm) interval overlapped with (warm). Additionally, (comfort) interval overlapped with (cool), (slightly cool), and (neutral) by around 13%, 20%, and 22% respectively. Considering winter set, the relatively narrower intervals reflected less variability. Yet, two overlaps occurred between (cool) and (slightly cool) and between (slightly warm) and (warm); their respective overlaps were 45% and 25% approximately with reference to (cool) and (slightly warm) intervals. Besides, it is noted that (neutral) was totally contained within (comfort) interval.

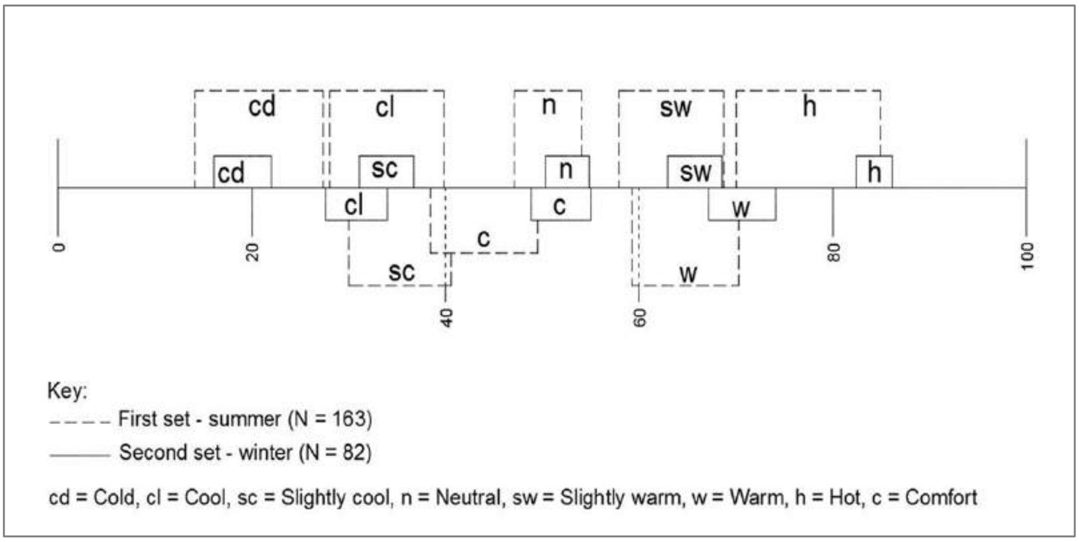


Figure 8. Distribution of means' 99% confidence intervals in the first and second sets

3.3. Thermal comfort equivalent

Relative frequencies of thermal sensations considered equivalent to (comfort) are depicted in Figure 9. In the total set, almost 67% of students considered the three central sensations equivalent to (comfort). In specific, 12%, 42%, and 12% approximately identified (slightly cool), (neutral), and (slightly warm) respectively as comfortable sensations. Their respective percentages were around 12%, 38%, and 9% in summer and around 13%, 51%, and 18% in winter. As noted, the total percentage of these three sensations dropped in summer by 24% approximately compared with that of winter, which may reflect seasonal influence. Indeed, almost 26% of students considered both (cool) and (cold) as equivalents for (comfort) in summer compared with only around 10% in winter.

Moreover, almost 63%, 64%, and 61% of students from the total, summer, and winter sets respectively considered (cold), (cool), and (neutral) as equivalents to (comfort). In a previous study, around 90% of Omani participants reported one of these sensations without expressing thermal discomfort (Abdul-Majid, et al., 2014). Yet, it should be mentioned that this study was conducted on 87 participants in two hot dry Omani cities.

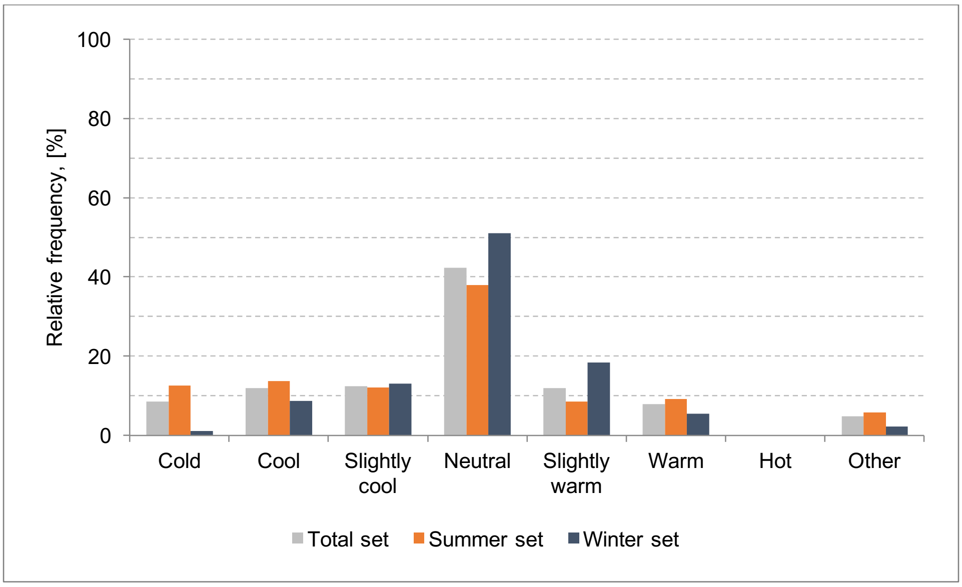


Figure 9. Relative frequencies of sensations equivalent to (comfort)

4. Conclusion

Translating English sensation phrases does not always convey the impressions associated with them. In this paper, the collective understanding of ASHRAE phrases was explored among Omani students by means of two questionnaires. It was found that the number of translated phrases for each sensation ranged between 7 and 44 and several translated phrases were common between sensations. This was mainly due to the features of the Arabic language. Moreover, the findings revealed that the phrases translated by students differed from the international translation. The students' differentiation between (slightly cool) and (cool) as well as (slightly warm) and (warm) was weak. This may be related to the students' level of knowledge besides the climatic nature of Muscat city. Additionally, students differentiated between (neutral) and (comfort). Estimating the sensations' means based on the season, it was found that the cool side means of summer were slightly hotter than their winter equivalences. The warm side means of the former season were relatively cooler than those of the latter. For most students, the three central categories represented thermal comfort with slight response to the seasonal influence.

The current translations of ASHRAE scale, including the international version, may convey desirable impressions outside the assumed comfort range. This may suggest developing Arabic thermal sensation scales or at least modify the current translations of ASHRAE scale. A suggested approach is to ask participants to list and classify all possible words that may be used to describe thermal sensations. Additionally, further investigations are required to explore the impact of using new phrases. For instance, phrases that are translated as (cool and not acceptable) and (warm and not acceptable) may be used instead of (cool) and (warm) to avoid possible desirable impressions. Besides, it is recommended to apply the implemented methodology on Western Arabs and other Eastern Arab groups to confirm and compare the findings.

Acknowledgment

Authors would like to express their gratitude to Sultan Qaboos University for funding the first author PhD study. Gratitude is also extended to the Ministry of Education in the sultanate of Oman for their support and the investigated schools for their participation.

5. References

Abdul-Majid, N. H. et al., 2014. Field survey of air conditioner temperature settings in a hot, dry climate (Oman). *HVAC & R Research,* 20(7), pp. 751-759

Al-Gharibi, H., 2016. Urbanisation and changing lifestyle patterns in Muscat. In: N. Sonja & A. von Richthofen, eds. *Urban Oman: Trends and perspective of urbanisation in Muscat capital area.* Zurich: LIT Verlag, pp. 73-79.

Al-Azri, N., Zurigat, Y. & Al-Rawahi, N., 2012. *Development of bioclimatic chart for passive building design in Muscat-Oman.* In: European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ), *International Conference on Renewable Energies and Power Qulaity (ICREPQ'12).* Santiago de Compostela, Spain, 28-30 March 2012, Santiago de Compostela: EA4EPQ

Alwetaishi, M. S., 2015. *Human thermal comfort and building performance of schools in hot and humid climate with a particular reference to Saudi Arabia, Jeddah.* PhD. University of Nottingham

Awajan, A., 2015. Keyword extraction from Arabic documents using term equivalence classes. *ACM Transaction on Asian and Low-Resource Language,* 14(2), pp. 7:1-7:18.

de Dear, R. J. & Brager, G. S., 1998. Developing an Adaptive Model of Thermal Comfort and Preference. *ASHRAE Transactions,* 104, pp 1-18

Farghal, A. & Wagner, A., 2010. *Studying the adaptive comfort model a case study in a hot dry climate, Cairo, Egypt.* In: Network for comfort and Energy Use in Buildings, *Adapting to Change: New Thinking on Comfort.* Cumberland Lodge, Windsor, UK, 9-11 April 2010, London: NCEUB

Givoni, B. et al., 2003. Outdoor comfort research issues. *Energy and Buildings,* 35(1), pp. 77-86

Harrison, A., 1988. Arabic pain words. *Pain,* 32(2), pp. 239-250.

Holes, C., 2004. *Modern Arabic: structures, functions, and varieties.* 2nd ed. Washington, D.C.: Georgetown University Press

Hoppe, P., 2002. Different aspects of assessing indoor and outdoor thermal comfort. *Energy and Buildings,* 34(6), pp. 661-665

Humphreys, M. A., 2008. *'Why did the piggy bark?' Some effects of language and context on the interpretation of words used in scales of warmth and thermal perference.* In: Network for comfort and Energy Use in Buildings, *Air Conditioning and the Low Carbon Challenge.* Cumberland Lodge, Windsor, UK, 27-29 July 2008, London: NCEUB

Humphreys, M., Nicol, F. & Roaf, S., 2016. *Adaptive Thermal Comfort: Foundations and Anaysis.* Oxon: Routledge

Konya, A. & Vandenberg, M., 2011. *Design primer for hot climates.* Reading: Archimedia Press Limited

Lee, J.-Y., Stone, E. A., Wakabayashi, H. & Tochihara, Y., 2010. Issues in combining the categorical and visual analog scale for the assessment of perceived thermal sensation: Methodological and conceptual considerations. *Applied Ergonomics,* 41(2), pp. 282-290

Mishra, A. K. & Ramgopal, M., 2013. Field studies on human thermal comfort - An overview. *Building and Environment,* Volume 64, pp. 94 - 106

Nicol, F., Humphreys, M. & Roaf, S., 2012. *Adaptive thermal comfort: Principles and practive.* Oxon: Routledge

Parsons, K., 2014. *Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort, and Performance.* 3rd ed. Boca Raton: CRC Press

Pitts, A., 2006. *The languages and semantics of thermal comfort.* In: Network for comfort and Energy Use in Buildings, *Comfort and Energy Use in Builsings, Getting them Right.* Cumberland Lodge, Windsor, UK, 2008, London: NCEUB

Ragette, F., 2012. *Traditional Domestic Architecture of the Arab Region.* Zlin: American Univeristy of Sharjah

Saiegh-Haddad, E., 2017. MAWRID: A model of Arabic word reading in development. *Journal of Learning Disabilities,* 1(9), pp. 1-9.

Saleh, S. Y. H., 2011. Evaluation *and enhancement of environmental performance of refugee shelters in Palestine.* PhD. University of Nottingham

Sayed, F., 2015. *A few surprising facts about the Arabic language.* [Online] Available at: https://www.britishcouncil.org/voices-magazine/surprising-facts-about-arabic-language [Accessed 28 February 2018].

Schweiker, M. et al., 2017. Challenging the assumptions for thermal sensation scales. *Building Research & Information,* 45(5), pp. 572-589

Shohan, A. A. A., 2015. *Thermal comfort and energy demand of small and large mosque buildings in Saudi Arabia.* PhD. University of Nottingham

Singh, M. K., Mahapatra, S. & Atreya, S. K., 2011. Adaptive thermal comfort model for different climatic zones of North-East India. *Applied Energy,* 88(7), pp. 2420-2428

Sufeljen, A. M. A., 2014. *Microclimate and thermal comfort of public enclosed courtyards in hor dry regions, with special reference to Tripoli, Libya.* PhD. University of Nottingham.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

What do people associate with "cold" or "hot"? - Qualitative analyses of the ASHRAE-scales' labels

Karin Schakib-Ekbatan[1,2], Susanne Becker[1,3], Antonina Cannistraro[2] and Marcel Schweiker[1,2]

[1] Heidelberg Academy of Sciences and Humanities, Heidelberg, Germany,
[2] Karlsruhe Institute of Technology, Germany, karin.schakib@kit.edu, marcel.schweiker@kit.edu
[3] Central Institute of Mental Health Mannheim, Germany, susanne.becker@zi-mannheim.de

Abstract: The ASHRAE-scale is often applied in the field of thermal comfort in order to evaluate occupants' perception of the built environment. Participants' ratings on the scale are considered as being comparable, based on the assumption that participants have similar associations with the labels of the scale. Because of the complexity of perception, this assumption can be questioned and it is worthwhile to scrutinize the usage of the scale. As qualitative component of an interdisciplinary experimental study the think-aloud-method was used to gather qualitative data regarding the associations with the verbal anchors of the scale: People were asked to mention whatever comes to their mind. A specific context, e.g. in terms of thinking of outdoor or indoor conditions, was not given in the instruction. 61 participants (32 females, 29 males) participated in interviews. Qualitative analyses show that most associations were linked to perception, seasons (winter, summer) as well as to inside/outside. The label 'neither cold nor warm' was mostly linked to indoor contexts such as private rooms and was considered as being difficult to describe. The results indicate that neglecting the variation of peoples' associations with verbal anchors of a scale might bear the risk of drawing wrong conclusions regarding the generalizability of the understanding of a scale.

Keywords: ASHRAE-scale, interviews, qualitative analyses

1. Introduction

In the field of thermal comfort and post-occupancy, a quantitative approach based on questionnaires is often applied in order to gather occupants' satisfaction with thermal comfort. It is assumed that the applied scales in those questionnaires are reliable and valid assessment tools and that they are equally understood by the respondents. The discussion, which scale fits best, was mostly done in the 1970s and further pursued in the 1980s (e.g. Rohles et al, 1989), but seems to become a current topic again (Fuchs et al, 2018; Lee et al, 2010; Schweiker et al, 2016; Van Someren et al, 2016).

The understanding of scales is a crucial issue because the results of surveys using scales lead to practical consequences e.g. the conditioning of indoor spaces such as the workplace. Thus, it is worthwhile to have a closer look at the very often applied ASHRAE-scale (2013) and on how people understand its verbal anchors. Due to the experiences that in addition to physical factors, perception of temperature is influenced by subjective needs and experiences psychological aspects were addressed in the 1970s (e.g. McIntyre, 1978) and 1980s (Sundstrom & Sundstrom, 1986b; Wineman, 1982). Rohles' (2007) concern regarding the ASHRAE-scale from a methodological perspective is, that the 7-point-scale (-3 to +3) with verbal anchors from cold to hot are more linked to sensation, while it is intended to measure comfort at the same time by interpreting the range of -1 to 1 as the range of comfort and the other points as discomfort. However, various studies show the gap between the PMV-model and direct votes indicate that this interpretation as comfort zone is not necessarily experienced by the occupants (Gao et al, 2015; Humphreys & Nicol, 2002; Schweiker & Wagner, 2015; Schweiker & Wagner, 2017). De Dear et al (1997) interpret differences in votes with respect to the ASHRAE-scale and the preference scale as a purely linguistic issue. In our opinion however, these two scales address two different aspects: the ASHRAE-scale as more related to the sensation of a stimulus and the preference scale as a more complex perception of the stimulus influenced by factors beyond physiological aspects.

A qualitative approach, collecting data by interviews, is sometimes applied as a supplement part of a quantitative survey regarding occupants' satisfaction (e.g. Goins & Moezzi, 2010; Shazad et al, 2013), but not regarding the questionnaire/instrument itself. Recently, Schweiker et al, 2016) scrutinized the ASHRAE-scale in terms of how participants perceive the distance of the scales' anchors to each other. The result revealed that the assignments of verbal anchors to the scales' line varied a lot and was not perceived constantly as being equidistant by the interviewees.

Thus, the rationale behind this study is to get insights into peoples' concept of thermal perception with respect to the verbal anchors of the ASHRAE-scale. This demands a qualitative approach: How do people make sense of their day-to-day experiences such as thermal comfort? Retrieving this knowledge affects the episodic memory which according to Tulving (1972; see also episodic (long-term) memory in Baddeley, 2001) is the ability to consciously recollect previous experiences from memory (e.g., recalling a recent situation regarding temperature such as ‚once hiking in the mountain in unsuitable clothes' or ‚swimming in the cold river Elbe in Saxony in march'). Making sense of the environment by creating concepts and categories as an essential (more intuitive, non-conscious as well as conscious) part of human perception (Sternberg and Sternberg, 2009). These cognitive processes are of importance for survival in order to quickly understand information from the environment, reacting or making decisions. Thus, classifying perceived stimuli from the environment, comparing them and forming concepts are relevant components of building autobiographic knowledge.

The qualitative approach based on interviews which aims to assess peoples' concepts of a phenomenon demands verbal skills, with thermal comfort as a day-to-day-phenomenon interviewees should be able (although on different levels) to comment on the verbal anchors. It can be assumed that people are familiar with the verbal anchors of the ASHRAE scale, due to their daily experiences with outdoor and indoor experiences (e.g. adjusting the heating) as well as comments from the media (e.g. weather forecasts).

This paper addresses the developed category scheme assorted to the interviewees' reported situations and experiences regarding the seven verbal anchors of the ASHRAE-scale. As usual for qualitative methods, hypotheses are not formulated.

2. Method

The presented study is part of a broader experimental study design aiming at detecting mechanisms of adaptation to thermal stimuli. Before starting with the procedures, the participants were informed about the study's terms, which had been approved by the local ethics committee, and gave written informed consent.

2.1. Subjects

Sixty-one healthy participants took part in the study. Participants were recruited using announcements placed on a local online job market for students and on the institutional homepage. All participants were above 18 years of age and assured to be either native speakers or to have a comparable language level in German. The participants were given a fixed allowance of 10 € per hour. The sample description is given in Table 1.

Table 1. Sample description

	Sex		**Age**	
N	**female**	**male**	**Mean**	**sd**
61	32	29	24.5	2.8

2.1. Data acquisition

The study was performed in the Laboratory for Occupant Behaviour, Thermal comfort, Satisfaction and Environmental Research (LOBSTER) belonging to the Building Science Group, Germany. The interviews took place in the anteroom (constantly conditioned) of the LOBSTER before experiments were conducted in an office of the climate chamber. In order to gather participants' understanding of the verbal anchors of the ASHRAE-scale, the think-aloud-technique (Boren & Ramey, 2000; Someren et al, 1994) was applied. It is a „research method in which participants speak aloud any words in their mind as they complete a task. A review of the literature has shown that think-aloud research methods (…) provide a valid source of data about participant thinking, especially during language based activities" (Charters, 2003, p. 68).

In order to collect the verbal material, an interview-guide was developed. The participants were asked to reflect on the verbal anchors by "speaking aloud", i.e. to verbalize their thoughts regarding the seven temperature labels of the ASHRAE-scale (cold, cool, slightly cool, neither cold nor warm, slightly warm, warm, hot). The instruction was: "Please describe a situation or experience that you associate with the several temperature ratings?" A specific context, in terms of thinking of outdoor or indoor conditions was not given. The interviews lasted up to 10 minutes for this question. The interviewers noted all verbalizations simultaneously (and as literally as possible), and were later used as bases of the analysis.

2.2. Data preparation and analysis

The verbal material from the open survey question was analyzed using the software MAXQDA 12. The explanation of the following important terms *code* and *category* of the qualitative methods is cited from Saldaña (2015): „A code in qualitative inquiry is most often a word or short phrase that symbolically assigns a summative, salient, essence-capturing, and/or evocative attribute for a portion of language-based (…) data" (p.4). Coding in this context is an interpretative and subjective act: "Coding enables you to organize and group similarly coded data into categories or 'families' because they share some characteristic – the beginning of a pattern" (p. 10).

The verbal material was translated from German into English. Iterative readings of the interviews were done by two coders in order to create categories inductively to condense the interviewees' comments.

3. Results

After reporting an overview of the codings, the major categories will be presented in detail, complemented by illustrative examples (quotations). For the detailed analyses of the categories the frequency of codings is given in the text when the number of nominations is five and higher. The verbal anchor *neither cold nor warm* will be illustrated as a map with all its facets of the codings because it turned out that the interviewees had difficulties to comment on this label.

3.1. Scheme of categories

In total 912 codings were assigned to the verbal material, leading to five major categories *clothing*, *location (inside, outside), perception, season/weather and temporal aspects* (see Table 2). Few comments that played a minor role in the interviews and had minor importance were subsumed in a *remainder category*.

Table 2. Scheme of categories in relation to the verbal anchors

Categories	Cold	Cool	Slightly Cool	Neither Cold Nor Warm	Slightly Warm	Warm	Hot	∑
Clothing	15	16	12	3	15	4	1	66
Inside	23	23	22	32	25	30	23	178
Outside	62	24	22	1	9	23	33	174
Perception	37	27	27	60	22	27	38	238
Season/ weather	33	33	27	8	28	28	30	187
Temporal Aspects	7	20	19	8	8	3	4	69
∑	177	143	129	112	107	115	129	912

Most codings are subsumed in the category *perception*, followed by *season/weather*, *inside* and *outside*. The category *perception* obtained most codings for the verbal anchor *neither cold nor warm* (see also Figure 3). *Inside* was mostly linked to this label as well, while outside was mostly associated with the label *cold*. Most codings in the category *season/weather* were connected to the endpoints of the scale and very seldomly to the middle verbal anchor.

Clothing and *temporal aspects* were mentioned less frequently in the interviews. *Clothing* was predominately related to the left part of the scale (cooler temperatures). Also *temporal aspects* were merely related to slightly cool and cool.

3.2. Clothing

Most comments were linked to clothing of the upper body (e.g. going outside in the morning without jacket or only in T-Shirt). The number of nominations regarding unsuitable clothing was related to the verbal anchors with the following frequency: *cold* (7), *cool* (8), S*lightly cool* (7), *slightly warm* (9), *neither cold nor warm* (-), *warm* (1) and *hot* (-) were rather not mentioned.

Exemplary quotations

Slightly cool:
"When I'm standing on the balcony in the morning only in T-Shirt" [1602ID]

„Around autumn in the evening, when putting on a sweater" [1601CC]

Slightly warm:
„Recently when I was on the train, I was dresses in rather too thick clothing." [1601HA]

„When I'm wearing a woolen sweater in a closed room...such as now." [1601AF]

3.3. Location: Inside and outside

Figure 1 illustrates the relation of the percentages for *inside* and *outside* showing the opposed distribution. The lines illustrate the trend of the distributions.

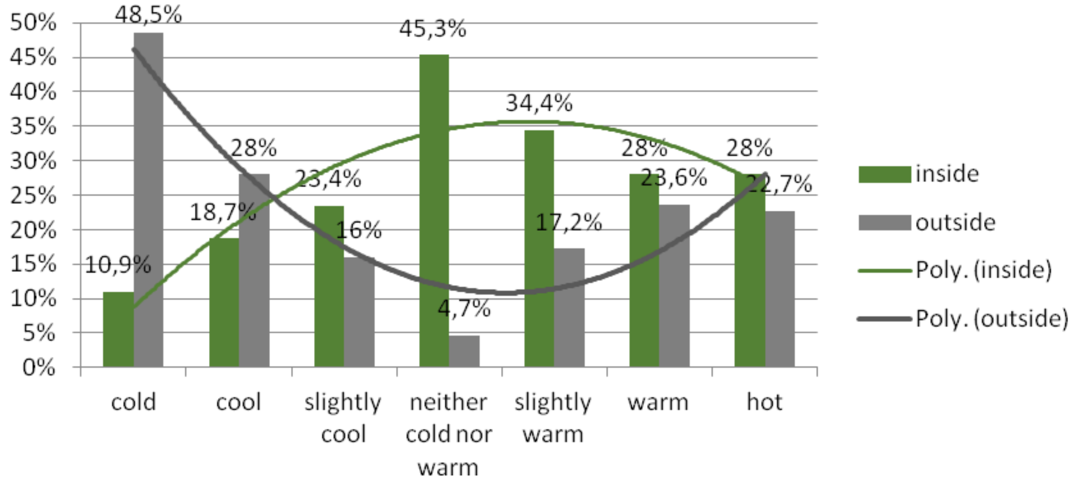


Figure 1. Percentage of nominations regarding *inside* and *outside* in relation to the verbal anchors

With overall smaller percentages, but similar frequency distributions as in Figure 1 specifications were reported as shown in Figure 2.

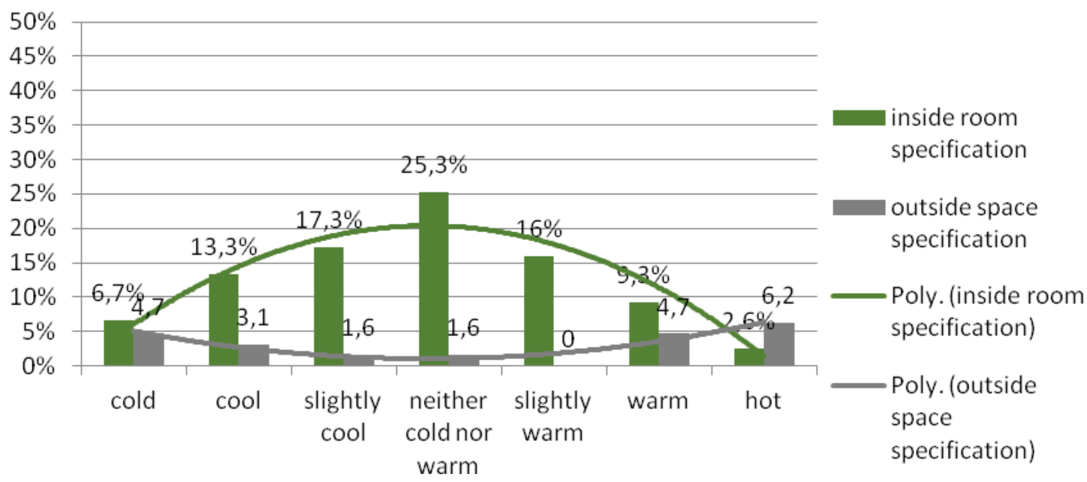


Figure 2. Percentage of specifications regarding *inside* and *outside* in relation to the verbal anchors

Inside specifications. Table 3 lists the codings related to Inside. The specifications are distributed over the whole range of the scale, including private rooms and rooms in non-residential buildings, specific areas of a building and cars. Open windows and draught are mentioned for cooler temperatures. The verbal anchor *neither cold nor warm* is mostly linked to residential buildings (6), the label *hot* was associated to the specification 'sauna' (14).

Table 2. Nominations regarding *inside* in relation to the verbal anchors

Category	Cold	Cool	Slightly cool	Neither cold nor warm	Slightly warm	Warm	Hot
Inside	• open window • draught • opening refrigerator • open window during night • at home • school • sportshall • office • floors • cold storage • non-residential buildings • airports • shopping malls	• sitting by the window • open window • sitting in draught • office • school • sportshall floors • cellar • freezer • opening the freezer • freezing department of supermarket • cinema	• open window when it's cold outside • natural ventilation too long • open window • sleeping • anteroom to office at home • school • university floors • rehearsal room (cellar) • shopping mall • freezing sector • tram • car	• at home • kitchen • office • university • car	• at home • penthouse • in bed • bathroom shower • office • working • library • anteroom of LOBSTER • on the train	• pent • house • kitchen/ cooking • by the chimney • in the bus • working in industrial hall	• penthouse • in bed • bathtube • shower • sauna • steelhall

Outside specifications. The category *outside* was split up in the subcategories *general*, *specified* and *activities* (Table 4). The most frequent general association in the context of *outside* was ‚snow' (12) for *cold* and ‚beach' (5) and ‚city' for *warm* and *hot*. Most specified associations such as geographically related nominations were reported in relation to the label *hot*. Activities such as skiing (6) played a role especially regarding the labels *cold* and *cool.* Also the actual experience ‚way to the LOBSTER' was mentioned several times.

Table 3. Nominations regarding *outside* in relation to the verbal anchors

Category	Cold	Cool	Slightly cool	Neither cold nor warm	Slightly warm	Warm	Hot
General	snow	-	-	-	-	beach	• beach • city
Specified	• in the mountains • Russia • Lappland	North America	• seaside • beach with fresh breeze	-	-	• lake • Bali at midnight	• Bali • Karlsruhe • Fidschi • Turkey • Asia • South of France • Southern countries • desert
Activities	• way to the LOBSTER • skiing-6 • camping • cycling • football game in winter • sitting for a long time • waiting for train/bus • swimming pool	• way to the LOBSTER-4 • cycling • swimming • sitting outside • barbecue • waiting for tram • driving home after having been outside allday	• going for a walk • hiking	going for a walk	• going for a walk • in the park	• sports • sitting at the campfire • skiing • swimming	• hiking • swimming • sightseeing

Exemplary quotations

Cold:
"Last holidays in Russia with -37°C." [160HC]

„In Saxony in March: there was snow and I went outside only in a thin jacket. Weather was super cold during the whole day, also inside. Or once when I went swimming in the Elbe." [1602BH]

Slightly cool:
"When we were hiking in the mountains...2500m high...I was dresses in summer clothing and it had only 0°C. First it was warm because of the movements, but then it got cold." [1602BA]

Hot:
„When I was in Bali, it was hot from 6am until 9pm." [1601AF]

„My last 6 months in Asia." [1602CF]

3.4. Perception

The codings were assigned to five subcategories: (1) HVAC, (2) *temperature*, (3) *transition* of experienced temperatures as perceived thermal conditions and general aspects, (4) *affective aspects* and (5) *body*.

HVAC, Temperature and Transition. Table 5 gives an overview of the codings related to these subcategories. HVAC is mentioned in relation to all verbal anchors, especially heating. The range of associated temperatures vary a lot within the several labels, e.g. 6°C to -37°C for *cold* or 25°C to 40°C for *hot*. Transition aspects are predominantly mentioned in relation to *cool* as well as in relation to *slightly warm*. No comments regarding transitional aspects were given for the label *neither cold nor warm*. *Cold* and *cool* were experienced as being similar nominations for temperatures.

Table 4. Thermal nominations in relation to the verbal anchors

Category	Cold	Cool	Slightly cool	Neither cold nor warm	Slightly warm	Warm	Hot
HVAC	• heating is off • extrem conditioning • heating not in function • under AC	• heating is off • AC • ventilator • before turning heating on • train with AC	• shop with AC • AC doesn't fit to season • heating is off	• AC • heating off before going to sleep	• heating is on • heating is too warm • turning heating on	• train without AC • heating is on	• not associated with heating • heating is too warm
Tempera-ture	• no difference between cool or cold • 6°C • >0°C • <0°C • ≤0°C • -10°C to -15°C • -17°C • -20°C • -30°C • -37°C	• <0°C: no difference between cool or cold • -15°C	• similar to cool • 10°C • 15°C • 17°C • 8°C to 15°C	• either cold or warm • typical room temp. • 20°C • 21°to 22°C • 22°C • 23°C • 23-25°C	• different to slightly warm • around 25°C • ≥25°C	• high air humidity • 22°C to27°C • 25°C to 27°C • 27°C to 28°C • 28°C to 29°C • 30°C • 30°C to 35°C	• high temp. • dry hot air • 25°C • ≥34°C • 30°C • 30°C or 35°C • 35°C • 40°C
Transition	• change from inside to outside	• weather changed • change from inside to outside • change from outside to inside • difference between temp. of water and air temp.	• wet, after shower • change from outside to inside • beginning of change in temp.		• increasing temp. • change in temp. • running stairs up/ getting into home • temporary sensation/ feeling • change from outside to inside	• change from cold to warm • not adapted to climate • change from outside to inside	• change from inside to outside • desire for shadow • accustomed to climate by home country

Slightly cool was also named as 'transitory state' and as being a 'moderate sensation'.

Affective aspects. The codings in Table 6 show that positive comments covered the labels cool to warm, while they were lacking for the endpoints of the scale. Only few negative comments were given regarding the middle verbal anchors (*slightly cool* to *slightly warm*), but more negative associations were connected with the endpoints, particularly especially for the label *hot*.

Table 5. Nominations regarding *affective aspects* in relation to the verbal anchors

Category	Cold	Cool	Slightly cool	Neither cold nor warm	Slightly warm	Warm	Hot
Affective Aspects	positive -	positive • pleasant • acceptable	positive • optimal • refreshing • acceptable • like it cool • still pleasant • like fresh air	positive • pleasant • ideal • well-being	positive • pleasant • pleasant • cosy	positive • pleasant • perfect • holiday feeling • similar to slightly warm	positive -
	negative • unpleasant • very unpleasant • uncomfortable weather	negative • desire for warmer temp. • slightly unpleasant • dislike • against expectation	negative • nasty	negative • not perfect	negative • negative • stress	negative • almost too warm • nervous • not optimal	negative • unpleasant • extremly unpleasant • extreme unbearable • nightmare • painful: soldering iron hotplate

Body. Comments of the interviewees were predominantly associated with the endpoints of the scale. Associated nominations with *cold* were freezing (6), feet, moderate pain, illness, and ears. Warm was associated with sun on the skin and sweating. For *hot* the highest number of nominations was sweating (5), other comments were 'difficulty to concentrate', ,sleepless', ,not able to move', after movement' and painful aspects such as soldering iron or hotplate.

Exemplary quotations

Cold:

„Is it only linked to temperatures? Also individuals can have a cold personality. Cold for me is as soon as I'm freezing, feeling unwell, when it's windy, when it has snow outside, when it's uncomfortable." [1601BA]

„Once in my youth I had a soccer match in March and it was raining and cold. I was the goal keeper and no ball was shot in my direction. At the end somebody made us wet with icy water from a creek. I have been ill for three weeks." [1601AF]

Slightly cool/slightly warm:

"Slightly cool and slightly warm more diffuse concepts than the others, but overall they are fitting quite okay." [1602FD]

„Slightly cool and slightly warm are vague terms. I don't think that this can be differentiated perceptually." [1601FH]

3.5. Season/Weather

As shown in Table 7 many comments were given to aspects of *season* and *weather*. In combination with *cold,* the highest number of codings was winter (25), also summer was mentioned. For *cool* all seasons were mentioned with most nominations for autumn (8), followed by summer (6) and winter (5). The *weather* was named e.g. as 'misty'. Summer (11) was the most mentioned season for *slightly cool*, followed by spring (6) and wind (6) as weather related aspect. Also *neither cold nor warm* was associated to seasons; one person reported that he/she is not thinking about weather regarding this verbal anchor. Spring (8) and sun (8) were the most mentioned nominations for *slightly warm*, followed by summer (5). *Warm* was to a higher extent associated with summer (18) and sun (9); this was comparable to *hot* with the nominations for summer (18) and sun (7). Humid climates were also associated with *hot*.

Table 7. Nominations regarding season/weather in relation to the verbal anchors

Category	Cold	Cool	Slightly cool	Neither cold nor warm	Slightly warm	Warm	Hot
Season/ Weather	• winter • spring • summer • autumn • damp weather • wind • snow	• winter • spring • summer • autumn • wind • rain • misty • getting fresh • snow	• spring • summer • autumn • begin of march • wind • rain in summer • sundawn • in the sun	• not extreme cold winterday • spring • autumn • rainy season • not thinking about weather	• spring • summer • autumn • sun • end of april • after Taifun	• summer • end of may • sun	• summer • august • sun • heat • humide climates

3.6. Temporal aspects

General and specific nominations were given in relation to *temporal aspects* (Table 8). Morning (6) and evening (5) were mostly associated with *cool*. The range of remembered time units varied: the very moment was associated with the situation inside the LOBSTER for almost all verbal anchors from *cold* to *warm*, with the highest number for *neither cold nor warm* (6) and *slightly warm* (7). Other comments referred to other parts of the day (e.g. 'this morning'), the day before, a week (e.g. 'last week'), as well as referring to a whole year. Especially *hot* was associated with a specific memory.

Table 8. Temporal nominations in relation to the verbal anchors

Category	Cold	Cool	Slightly cool	Neither cold nor warm	Slightly warm	Warm	Hot
General	mornings	• mornings • evenings • nights	• nights • sundawns • evenings • getting up	seldom	-	at noon	-
Specified	• right now • earlier on • yesterday • last week	right now	• this morning • the last nights • yesterday evening in open air cinema • this year was cool	• right now • not felt today	right now	right now	• yesterday noon • last Saturday • Karlsruhe last year • last year was rather hot in Germany

3.7. Remainder codings

Some comments can be characterized as linguistic aspects.

Exemplary quotations

Cool:
(‘kühl’ in German): “klingt wie Kühlschrank/Kühlhaus“ [1602GE]

(translation: “sounds like freezer/cold storage”)

Slightly warm:
“Slightly sounds as being unpleasant, too much, e.g. too much stress [1601IB]

Other nominations were related to cold (‚cold drink’, ‘ice cubes’), to neither cold nor warm (‘wood’, ‘tree’) and to hot (‚tea‘, ‚boiling water‘).

3.8. Map of the verbal anchor *neither cold nor warm*

The verbal anchor *neither cold nor warm* is illustrated by a map with its categories in Figure 3. Nearly all major categories are covered, except *transition* and *body*. Most codings are related to *inside*, typical indoor temperature and positive affect.

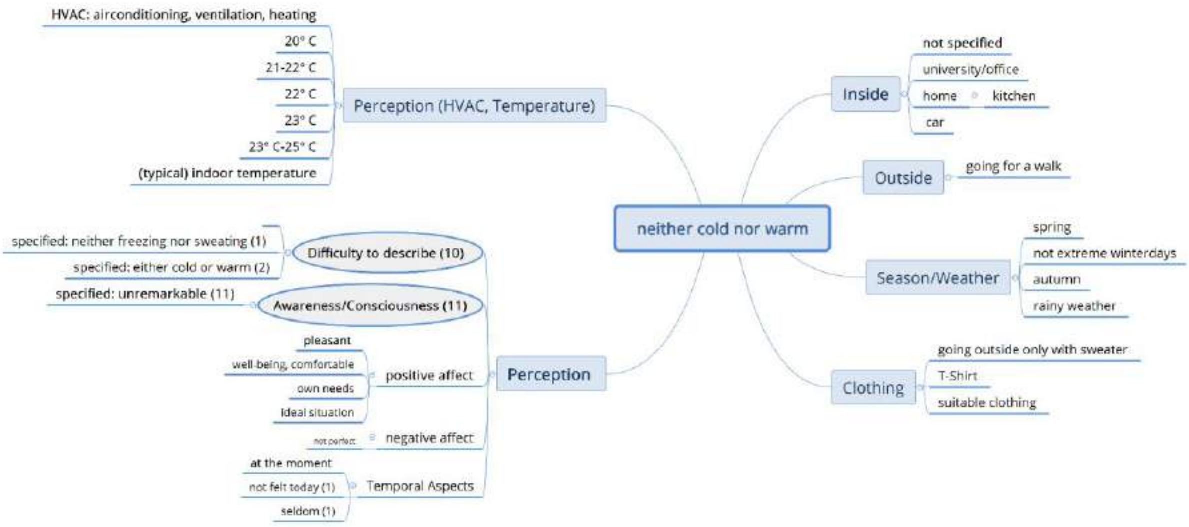


Figure 3. Mapping of the codings related to the verbal anchor *neither cold nor warm*

In contrast to all other labels, the interviewees (around 24%) indicated to have problems to comment on this verbal anchor. The major difficulty mentioned was that they perceived this sensation as not remarkable. The following exemplary quotations show different aspects of the interviewees' comments such as theoretical problems [1602AG, 160115], methodological aspects [1602GE], wording [1602AA, 1602GD], meaninglessness [1602AA, 1602FC], definite priority of sensation [1602EC], and negative affect [1601CC].

Exemplary quotations

"Neither cold nor warm, that is not definable, for some it is rather warm, for others cold." [1602HF]

„Neither cold nor warm is actually no temperature...cannot be described theoretically." [1601AG]

„Neither cold nor warm …that is a double negation, that is no positive statement." [1602AA]

„It should actually be named neither cool nor warm: It is a mess of the terms cold, cool hot, warm." [1602GE]

"The label doesn't fit, people wouldn't use it, when asked if it is cool or warm." [1602GD]

„Neither cold nor warm is vague, meaningless…what does it mean: lukewarm, icecold? The meaning is only understandable by the order of the labels." [1601BA]

"Difficult, neither cold nor warm is a bit meaningless. I would rather give a temperature." [1602FC]

"Neither cold nor warm is pleasant, but one would chose a priority: warm/pleasantly warm or cold/pleasantly cold." [1602EC]

„I don't know this sensation, nor do I want to get to know it!" [1601CC]

4. Discussion and conclusions

The qualitative approach by applying the think aloud technique brought first insights into the participants' concepts of thermal comfort aspects. The analysis of the interviews based on an open question regarding situations and experiences with the verbal anchors of the ASHRAE scale revealed the broad range of peoples' understanding of the scale. The obtained comments regarding the labels varied from a concrete level (specific situations or experiences, temperatures) to an abstract level (e.g. '*transitory state', methodological or linguistic aspects).* Episodic memory was mostly linked to extreme temperatures.

The codings could be grouped in meaningful categories of which some were expectable in relation to thermal aspects such as nominations with a more objective character (*clothing, inside, outside, season/weather*). Some nominations showed relation to parameters of the PMV-Model: temperature, draught, clothing, met (e.g. activities) or air humidity. Clothing (merely for the upper body) as a coping strategy was often mentioned as being unsuitable and in combination with the verbal anchors *cold*, *cool* and *slightly cool* and was no topic in combination to warmer temperatures probably because the effect on the thermoregulation is limited. 'Sauna' was very often mentioned in combination with the label *hot;* at the same time there were no positive associations reported with this label. It can be assumed that using the sauna would be a positive experience, thus the lacking of positive affects related to *hot* could mean that the nomination of 'sauna' was as simple association rather than be based on experience.

Another group with a large number of codings was *perception*. The comments showed pronounced subjectiveness regarding perceived temperatures in combination with the verbal anchors. The striking observation that aspects of *transition* were not mentioned in relation to *neither cold nor warm* could support the discussion regarding alliesthesia, (De Dear, 2011; Schweiker et al (n.d.)), in terms of desire for stimuli (e.g. ameliorating the inner state by a pleasant stimulus). Nominations regarding *affective aspects* showed that extreme temperatures were negatively connotated. For *temporal aspects* the episodic memory played a role for a broad range of time periods, reaching from the very moment to a year which has relevance for corresponding items in questionnaires.

The verbal anchor *neither cold nor warm* turned out to fall out of the series of labels from the perspective of the interviewees. A quarter of them expressed difficulties to comment the label, because they considered the intended sensation as unremarkable. This raises the question of awareness and how reliable votes can be held regarding a stimulus, which is perceived as being absent. This is in line with findings from interviews regarding pain, which is another focus of the present study (Schakib et al, 2017). Further explanations addressing methodological or theoretical issues are worthy of consideration for further research on the scale. If people have problems with a verbal anchor that refers to everyday terms such as cold or warm, it can be assumed that understanding respectively commenting on the scientific term *neutral* (original ASHRAE-scale) could be even more difficult for interviewees. It can be questionned if it is useful for interviewing lay people.

Although the sample size can be considered as large in the context of qualitative research, some restrictions have to be mentioned. Firstly, methodological aspects: Due to time pressure within the study procedures for the participants, the interviewers did not follow-up to details regarding the participants' comments. The method think-aloud-technique, aiming at bringing people to reflect and speak, may triggers intentional thinking and thereby a form of "story-telling", a known phenomenon in psychology when people are forced to come up with explanations of processes they often not aware of (Nisbett &

Wilson, 1977). Because of data-protection-issues, the interviews were not audio or video-taped, leading to the lack of additional information such as nonverbal aspects from the interviewees. The process of interpreting the interview material cannot lead to a completely congruent understanding between interviewee and interviewer, because she/he her-/himself brings in his own worldview and knowledge about the topic of the interview. As coding is a subjective process, other codings or categories might have been created. The coding process of the two coders was matching well. Secondly, topic-related issues have to be addressed: The question regarding situations or experiences was not focused on specific environments such as inside or outside which could be helpful in order to get more differentiated insights leading to practical implications.

The results of the present study reveal first insights into peoples' concepts with respect to verbal anchors of a scale often used in the field of thermal comfort. The approach brought up some discussable issues of the ASHRAE-scale. They raise the question: To which extent can we generalize the votes from the questionnaires when people have so different under-standing of verbal anchors?

In order to derive specific recommendations the next research steps will be to conduct in-depth interviews regarding the understanding of scales as well as to combine qualitative and quantitative data regarding thermal perception in order to detect patterns which can be useful for theoretical discussions as well as for practitioners.

5. References

ASHRAE, 2013. Standard 55-2013. *Thermal environmental conditions for human occupancy*. American Society of Heating, Refrigerating and Air-Conditioning Engineering, Atlanta, USA.

Baddeley, A., 2001. The concept of episodic memory. *Philosophical Transactions Of The Royal Society Of London Series B - Biological Sciences*, 356(1413), pp. 1345-50. DOI: 10.1098/rstb.2001.0957

Boren, T. & Ramey, J., 2000. Thinking aloud: reconciling theory and practice, *IEEE Trans. Prof. Commun*. 43, pp 261–278. Doi:10.1109/47.867942.

Charters, E., 2003. The Use of Think-aloud Methods in Qualitative Research. *Brock Education*, 12(2), pp 68-82.

De Dear, R.J., 2011. Revisiting an old hypothesis of human thermal perception: alliesthesia. *Building Research & Information*, 39(2), pp 108–117.

De Dear, R.J., Brager, G.S. and Cooper, D., 1997. Developing an Adaptive Model of Thermal Comfort and Preference. In: *Final Report on ASHRAE Research Project 884*. Macquarie University Sydney.

Fuchs, X., Becker, S., Schakib-Ekbatan, K. & Schweiker, M., 2018. Subgroups holding different conceptions of scales rate room temperatures differently. Building and Environment, 128, pp 236–247. Doi.org/10.1016/j.buildenv.2017.11.034.

Gao, J., Wang, Y. & Wargocki, P., 2015. Comparative analysis of modified PMV models and SET models to predict human thermal sensation in naturally ventilated buildings. *Building and Environment*, 92, pp 200–208.

Humphreys, M.A. & Nicol, F., 2002. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy and Buildings*, 34(6), pp 667–684.

Goins, J. & Moezzi, M., 2010. Links between occupant complaint handling and building performance In: *Rethinking Thermal Comfort*. Windsor conference, Windsor, UK, 12-15 April 2010.

Lee, J.-Y., Stone, E.A., Wakabayashi, H. & Tochihara, Y., 2010. Issues in combining the categorical and visual analog scale for the assessment of perceived thermal sensation: Methodological and conceptual considerations. *Applied ergonomics*, 41(2), pp282–290.

McIntyre, D.A., 1978. Seven point scales of warmth. Building Services Engineering Research and Technology, 45, pp 215–226.

Nisbett, R.E, Wilson, T.D., 1977. Telling More Than We Can Know: Verbal Reports on Mental Processes. *Psychol. Rev*, 84, pp 231–259.

Rohles, F.H., 2007. Temperature & Temperament: A Psychologist Looks at Comfort*, ASHRAE J*. 49, pp 14–22.

Rohles, F.H., Woods, J.E., and Morey, PR., 1989. Indoor Environment Acceptability: the Development of a Rating Scale, *ASHRAE Transactions*, 95, pt. 1, pp 23–27.

Saldaña, J. (2015). *The Coding Manual for Qualitative Researchers* (3rd ed). Los Angeles: Sage.

Schakib-Ekbatan, K., Becker, S. & Schweiker, M., 2017. Does "painful" or "hot" mean the same to different people? *HAW-Symposium 'Perception of thermal comfort and pain - are we assessing their dynamics right?'*, Heidelberg, Germany, 9-11 November 2017

Schweiker, M. and Wagner, A., 2015. A framework for an adaptive thermal heat balance model (ATHB). Building and Environment, 94(P1), pp 252–262.

Schweiker, M. & Wagner, A., 2017. Influences on the predictive performance of thermal sensation indices. Building Research and Information, 45(7), pp745–758.

Schweiker, M., Fuchs, X., Becker, S., Shukuya, M., Dovjak, M., Hawighorst, M. & Kolarik, J., 2016. Challenging the assumptions for thermal sensation scales, *Building Research and Information, 45(5), 572-589.* Doi:10.1080/09613218.2016.1183185.

Schweiker, M., Becker, S. & Schakib-Ekbatan, K. (to be deciced). In: *Rethinking Thermal Comfort*. Windsor conference.

Shazad, S.S. Brennan J. & Theodossopoulos, D., 2013. Quantitative vs. Qualitative Methodologies to Investigate Environmental Control in the Workplace: Neutral Thermal Sensation and Thermal Environmental Intention. PLEA, 29th Conference Sustainable Architecture for a Renewable Future, Munich, Germany, 10-12 September 2013.

Someren, W. M., Barnard, F. Y., & Sandberg, A.C. J., 1994. *The think aloud method. A practical guide to modeling cognitive process.* London: Harcourt Brace & Company.

Sternberg, R.J. & Sternberg, K., 2017. *Cognitive Psychology* (7th ed.). Boston, MA: Cengage.

Sundstrom, E. & Sundstrom, M. G., 1986b. *Work Places: the Psychology of the Physical Environment in Offices and Factories*. Cambridge: University Press.

Tulving, E., 1972. Episodic and semantic memory. In E. Tulving and W. Donaldson (Eds.), *Organization of Memory* (pp 381–402). New York: Academic Press.

Van Someren, E.J.W., Dekker, K., Te Lindert, B.H.W., Benjamins, J.S., Moens, S., Migliorati, F., Aarts, E. & van der Sluis, S., 2016. The experienced temperature sensitivity and regulation survey. *Temperature*, [online] 3(1), pp 59–76. Available at: <https://doi.org/10.1080/23328940.2015.1130519>.

Wineman, I., 1982. The office environment as a source of stress. In G. W. Evans (Ed.), *Environmental stress* (pp. 256-285). New York: Cambridge University Press.

WORKSHOP 2

Overheating

Invited Chairs:
Runa Hellwig and
Wouter van Marken Lichtenbelt

Variance of future UK heat wave incidents with geographic implications on mitigation

Asif Din[1] and Luisa Brotas[2]

[1] Cass School Art, Architecture and Design, London Metropolitan University, London. UK aud0034@my.londonmet.ac.uk;
[2] Cass School of Art, Architecture and Design, London Metropolitan University, London. UK l.brotas@londonmet.ac.uk

Abstract: The effect of heat waves on human comfort is an area of research that needs to be further investigated. Many of the parameters that deal with heat wave events have similar mitigation strategies to those used for overheating. This study examines weather files from 8 UK cities to identify heat wave periods which are then used to quantify the effectiveness of shading and thermal mass in a simulated prototype. Both heat wave and cooling season results are compared to highlight the differences in their characteristics. The effect of thermal mass and fixed shading in the building, based on a previously used prototype model, is assessed with EnergyPlus software. Results show that the number of heat wave days have no correlation with the city's population, a possible proxy for the heat island effect. A combination of thermal mass and shading can be 90% effective in reducing the impact of a heat wave event. The next best solution is thermal mass, then shading alone, which reduces heat wave impact by up to 50%. These roughly follow the results obtained for the cooling season but the proportion of overheating criterion given in TM52 for the cooling season and heat wave events show little relationship and require further investigation.

Keywords: Heat Wave mitigation, TM52, TM59, Future Climate, Overheating mitigation

1. Introduction

Heat waves are particular weather characteristics that may significantly influence the internal environment of buildings, but have not been given much thought in previous research. There is a lack of standards or guidance relating to the parameters and methodology required to model such occurrences. Designers should consider heat wave effects within their building design, as previous events have demonstrated they have a strong impact the comfort and well-being of building occupants.

Heat waves are by definition abnormal events that occur in the external environment. There will be an increase in the frequency of heat waves, as external temperatures and the temperature extremes rise in the future. The UK definition of a heat wave relates to emergency response plans (NHS, 2015) and is different from the international identification of a heat wave event. A conservative estimate derived on a previous study predicts a tenfold increase in heat wave occurrences in 60 years' time (Din and Brotas, 2016). This coincides with the lifespan of current new buildings according to the Building Research Establishment (BRE, 2018).

The particular impact of heat wave effects on occupants in comparison to (dis)comfort levels experienced in the rest of the cooling season has not been quantified in previous building studies. A key parameter in the definition of the building's thermal characteristics is the thermal capacity (mass) of the construction materials. This parameter has been shown to reduce heating and cooling requirements, as it acts as thermal storage reducing peak temperatures (CIBSE, 2016) and dissipating heat energy (Hacker, 2008).

The mitigation of heat waves follows the same strategies used to prevent overheating (ZCH, 2012). The three factors that have the most impact in minimising overheating in buildings are thermal mass, shading and air velocity. Modifying the air velocity was not considered in this study because the ceiling height of new build dwellings in the UK is too low to be effective for ceiling fans (passipedia, 2018). These would require higher floor to ceiling heights to allow for an effective velocity downdraft. Raising ceiling heights is not realistic in the current housing construction market in the UK, which is interested in maximising profit through dwelling density. The main priority has become cutting heat losses through the fabric, to reduce CO2 emissions in the heating season as a requirement of building regulations and planning applications.

Previous studies have shown the impact of shading on comfort (Din and Brotas, 2016) but do not take into account the combined effects of mitigating measures with thermal mass. Providing additional solutions may affect the overall mitigation result in a non linear manner. The use of mitigation measures may not be applicable in all the UK as it depends on individual local conditions. Although the UK is classified as one climate by ASHRAE (2018), building regulations define separate regions with different characteristics. Any overheating mitigation measure used should be defined according to its geographic significance.

Building designers should assess the resilience of the building over its lifespan (Jenkins et al, 2012) with the onset of climate change. Overheating and particularly extreme high temperature heat wave events will have a critical impact on the comfort of (alongside health dangers to) occupants within the lifespan of the building and their risk within a building design should be assessed.

The starting point to assess heat waves is to use current methods of assessing overheating such as BSEN 15251 (BSi, 2007), complemented by the Chartered Institute of Service Engineers (CIBSE) Technical Memorandum TM52 (2013). TM52 does not provide a definitive operative threshold but a range of conditions taking into account occupant's acclimatisation, i.e. adapting their comfort with historic weather conditions. The CIBSE Technical Memorandum TM59 (2017) adds to the previous methodology the definition of the parameters for equipment, occupancy and occupancy hours in dwellings. TM59 assesses the risk of overheating for a range of units within a housing development.

2. Aims

This study shows the variance in heat wave patterns from future climate files for different UK locations in different zones as defined by the UK building Regulations Standard Assessment Procedure, SAP (DECC, 2012). The main part of the study assesses the thermal mass and shading input to simulation software (Energy Plus v8.7.0).

The study shows the amount of overheating occurring under heat wave events in 2080 provides a future end point for new buildings and maximises the number of overheating events experienced. The weather files are from the Eames et al studies (2012) which have established probabilistic weather for future years based on climate change models for various locations in the UK. The study will show the impact of shading and thermal mass which are already recognised as overheating mitigation measures. The comparison of the impact of heat wave events on the internal comfort of occupants in comparison with the whole of the cooling season will show what types of overheating (as defined by TM52) are significant and any relationships that occur in terms of impact of mitigation and the geographic location within the UK.

3. Background

The assessment of overheating in the UK building regulations SAP is based on a simple calculation using climate data, the construction materials and solar gains. The internal environment of dwellings demands better criteria than a simple threshold temperature (Beizaee et al, 2013). Regulatory tools should assess the impact of heat waves. Despite their short term they have a disproportionately large impact (McLeod et al, 2013) to the comfort and well-being to the building occupants.

Previous overheating studies assessing the internal conditions of dwellings do not consider heat waves. Similarly, many heat wave studies do not quantify the heat wave impact on comfort of occupants inside a dwelling. TM52 assesses overheating using the adaptive comfort methodology, where the comfort temperature depends of the outdoor temperature rather than a fixed threshold temperature. Overheating is assessed accounting for the proportion of uncomfortable conditions that are experienced by building occupants. This is a development of the previously defined BS EN 15251 guidance. TM52 sets a relationship between the outside temperature, the occupant's behaviour, the activity and adaptive opportunities which affect comfort. Overheating is defined in three distinct criteria which have some interdependency in their calculation method:

1. The amount of degree hours more than 1K over the limiting comfort temperature (assessed from 1st May to 30th September) must be less than 3% of occupied hours;
2. The higher the temperature the more significant the overheating effect. This test quantifies the severity of temperature on a daily basis. The weighted excess of temperature must be less than 6 degree-hours on any one day for comfort to be achieved;
3. Reports heat stress events 4K above the limiting comfort temperature.

Occupants are likely to experience overheating if two or more of these conditions are not met. TM52 defines the amount of overheating over the whole cooling season. The conditions given above need modification to allow the comparison of short time periods with those over the whole cooling season

TM59 defines the model input requirements and technical specifications to assess the risk of overheating in a housing development. The guidance uses the TM52 classifications of overheating but also defines the type and future climate files to use to assess overheating risk. The guidance also defines a range of other influencing factors including setting the temperatures windows should be operated, the occupancy rates, schedules and specification of equipment allowed for each room. The guidance also specifies a fixed set point temperature similar to that used in BS EN 15251 for use in bedrooms. TM59 is good in defining aspects but a range of double accounting exists to increase the probability of identifying overheating risk. However, it does not provide the quantification of overheating which has been further developed in this paper. This study uses the TM59 as the backbone of model inputs but some inputs have been modified to give more realistic results. With such twofold inputs any errors will be internal to the simulation process and will not prevent a comparison between models in this paper.

Climate change model scenarios for low, medium, and high probability were retrieved from the Eames et al weather database. Each file has a 33, 50, 66 and 90th probabilistic percentile depending on the risk being assessed. Files are available in 20 year bands from a reference year to 2080. The climate output files are available in two forms of future weather files. Test Reference Year (TRY) which uses averages from the previous 20 years of data to produce a weather file and the Design Summer Year (DSY) uses 20 years of the peak summer condition to weight the weather file. From this range of options care has been taken to select the right file for use in this study.

Din and Brotas (2016) have shown for a case study in London that active cooling to prevent overheating in bedrooms is predicted to happen in the near future. The variation in overheating within living rooms is sensitive to daytime room occupation and solar gains. This creates the opportunity for the further investigation of the combination of overheating mitigation strategies as previously identified by the Zero Carbon Hub.

Heat wave weather periods have a relationship to mortality events (Zhang et al, 2013). Many major urban centres have defined a trigger temperature to activate the emergency services plan (Diaz et al, 2015). Studies have been conducted to classify inhabitants by location and social demographic to identify their vulnerability to heat wave events (Wolf and McGregor, 2012) for a trigger temperature of 28^{o}C. Existing heat wave definitions vary depending on geographic locations ranging in peak daytime temperatures from 26^{o}C to 40^{o}C (Scandinavia to Australia respectively) and a variance in the duration of days these temperatures are experienced from a daytime single event to being averaged over a specific number of consecutive days. Other heat wave definitions include night-time temperatures as part of the assessment occurring before or after the daytime threshold level to be classified as a heat wave.

Dense built up areas can aggravate the Heat Island Effect and rise of night time temperatures (Lemonsu et al, 2014). The current heat wave plan for England (NHS, 2015) defines a set point temperature of 32^{o}C for the day if the night before the temperature of 18^{o}C is exceeded. This threshold is an emergency response threshold and may be considered too high for a comfort analysis. Previous heat wave studies show actual observed data from a historic viewpoint (Porritt et al, 2012) as heat waves are defined as extreme random events historical data is currently the only methodology used to analysing such events. No studies define heat wave effects using future climate files.

A literature review on the influence of heat waves on the built environment is mainly concerned with the external urban environment rather than internal occupied areas. The built infrastructure influence on heat wave susceptibility for Europe is examined in Hintz et al (2017). The study identified the UK as the country most influenced by the 'grey infrastructure' that includes the external characteristics such as dark surfaces and green roofs and occupant behaviour, although these factors are not quantified.

The urban heat island of a site is compared to a surrounding countryside by Ward et al (2016). Comparative studies in Northern and Southern Europe show that urban heat island can be alleviated by urban green spaces. In Shanghai the building density and its elevated height create hot spots within the urban context (Chen et al, 2016).

The quality of the built environment is studied by Kim and Kim (2017) in which poor building standards are linked to higher heat wave events in deprived urban temperatures in Seoul, South Korea. These external studies are summarised in a study into heat wave mitigation strategies used in urban environments (Salata et al, 2017).

An inhabitant centric study conducted by Norbert and Pelling (2017) explores the vulnerability to discomfort. The study has been conducted using qualitative interviews to assess the speed of mitigation adoption amongst residents. Residents were given a range of external information such as television news reports. Elderly people were the least aware and tend not to modify their behaviour in a heat wave period, with possible negative health consequences.

Heat wave events are extreme events and have a low quantification within weather files which are based on 20 year averages. If a heat wave is identified to occur within a weather file then this would occur for every individual year within that 20 year sequence. Heat wave events defined by present-day standards will increase 20 fold by 2080 with one heat wave event a year as early as 2020 (Din and Brotas, 2017). Heat wave events that are quantified for 2080 may occur for a single year within the 2040s based on historic heat wave event projections.

The differences between Heathrow and Islington data in Din and Brotas (2016) leads to questions on the reliability of future weather files and the significance of consistently longer hotter periods evidenced in the Heathrow future projected data. This requires further investigation of the weather files and the Heat Island effect through geographic and population data.

4. Methodology

A typical flat layout shown in Figure 1 has been used in previous studies (Din and Brotas, 2016) as an archetypal model. The dynamic thermal software of Energy Plus 8.7.0 is used to simulate the internal temperatures which has been validated for the calculation of thermal mass effects by US department of Energy (2014) using the TARP algorithm within the energy balance calculations.

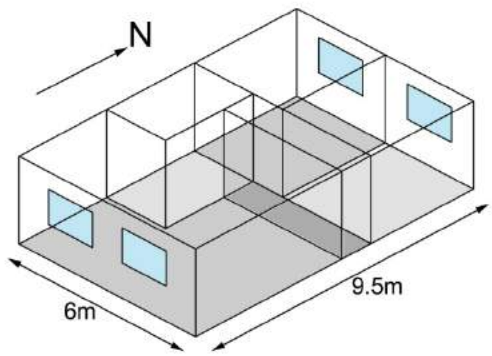


Figure 1. Two bed Flat configuration and dimensions

In the paper only the south facing living room is assessed with the rest of the flat providing adjacent spaces in which some thermal and radiative heat exchange occurs during non-occupied hours. The energetic configuration and loads need to be compared with TM59. Occupancy is identical apart from 3 people occupying the space from 7am to 7pm and then 2 people from 7pm to 11 pm to model a child going to bed. TM59 in contrast models continuous occupancy in the whole dwelling simultaneously in bedrooms and living areas.

The ventilation control is set to close the windows when the outside temperature is 5K higher than inside temperature. The lower limit when windows are also assumed closed is set to 18^{o}C rather than 22^{o}C as in TM59. Restrictors for night ventilation are in line with TM59.

The construction follows the specification of a PassivHaus: U value equivalent of 0.15 W/m^{2}K and an air tightness of 1m^3/m^2/hr. Internal Heat Gain (IHG) from people and lighting are in line with TM59 but appliances and their usage are given in more detail. Cooking occurs for 1.5 hours a day using a 1700W ceramic hob. Domestic appliances are taken from PassivHaus Planning Package (passipedia, 2018) at 210W for 10 hours a day.

Each modelled flat is applied with lightweight plasterboard to its innermost face as the base case. A 100mm dense concrete on the inner face acts as a thermal mass surface to the interior space (CIBSE, 2016), to model its effect. The density of thermal mass used was 2200kg/m^3 in line with CIBSE recommendations. Both models have similar windows and insulation levels. A 1 meter horizontal overhang to the whole of the south facade is applied to each model to determine the effect of shading on the results obtained.

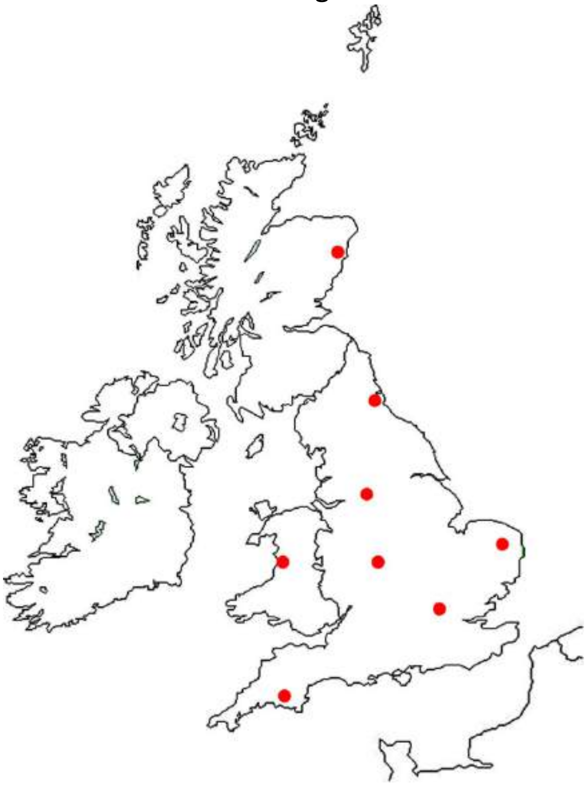


Figure 2. 8 cities investigated in the study. Each within a different weather zone in SAP

From future weather files (Eames et al, 2012) heat waves were identified in the 2080 high IPCC climate change scenario (business as usual), 66th percentile probabilistic data.

This is slightly higher than the 50th percentile recommended in TM59 but was used as the overheating demonstrated by 90th percentile has been shown to be exponentially higher than the 66th percentile weather files (Din and Brotas, 2017). Overheating is evaluated for the whole cooling season using Design Summer Year weather files in line with TM52 recommendations.

The process is carried out for 8 cities within the UK in differing weather zones as identified within the SAP methodology shown in Figure 2. These were Aberdeen 16, Aberystwyth 13, Birmingham 6, London (Islington) 1, Manchester 7E, Newcastle 9E, Norwich 12 and Plymouth 4. Each of the number codes beside the city specify the weather zone in SAP from 1 to 16. The building life is not relevant to this study however the dates for analysis coincide with that of the life of a new building, i.e. 60 years using BRE/NHBC guidelines.

Heat wave events are identified within the weather files and overheating is quantified for the 4 different construction models (lightweight, heavyweight with and without shading) for each city over any day that reaches over 28^{o}C and 18^{o}C the previous night. This follows a sensible day temperature definition from previous literature and the night time given from NHS guidelines. These periods match historic heat wave events in weather files. Discrete days and series of days are dealt with in the same way.

The cooling season is defined from 1st May to 30th Sept in line with TM52 guidelines for the 4 construction models and 7 cities within the UK. Each of the TM52 conditions is quantified on temperature frequency of the interior living room. This is a modification of TM52 but allows a comparison of the whole cooling season with a heat wave event, so that the criteria are modified to:

1. hourly above a threshold comfort temperature (hrs);
2. Amount of days over the daily weighted threshold of 6 deg-hrs (w);
3. number of hourly instances above the adaptive heat stress temperature (no).

This study deals with the quantification of each of the criteria, not requiring two conditions to be met to account for overheating. The time element is eliminated so not requiring annual occupied hours.

In summary heat wave periods are identified for 7 cities and compared to their population. Four construction types are modelled: lightweight (L), lightweight with shading (LS), heavyweight (H) and heavyweight with shading (HS). These are modelled over the heat wave periods for each of the modified TM52 criteria and then over the cooling season and the results compared. A comparison is made between the differing TM52 conditions previously identified. This is given as a proportion of the whole TM52 quantification in each case, to ascertain whether patterns on the conditions of TM52 that can be characterised for a heat wave period compared to that of a cooling season.

5. Results

Heat wave periods retrieved from the weather files are presented in figure 3. The number of days were plotted against the population of each of the cities to see if any relationship existed between the data. The population being a reasonable proxy against heat island effect the more populated the area the more hard surfaces and therefore a differential between the city and the surrounding countryside.

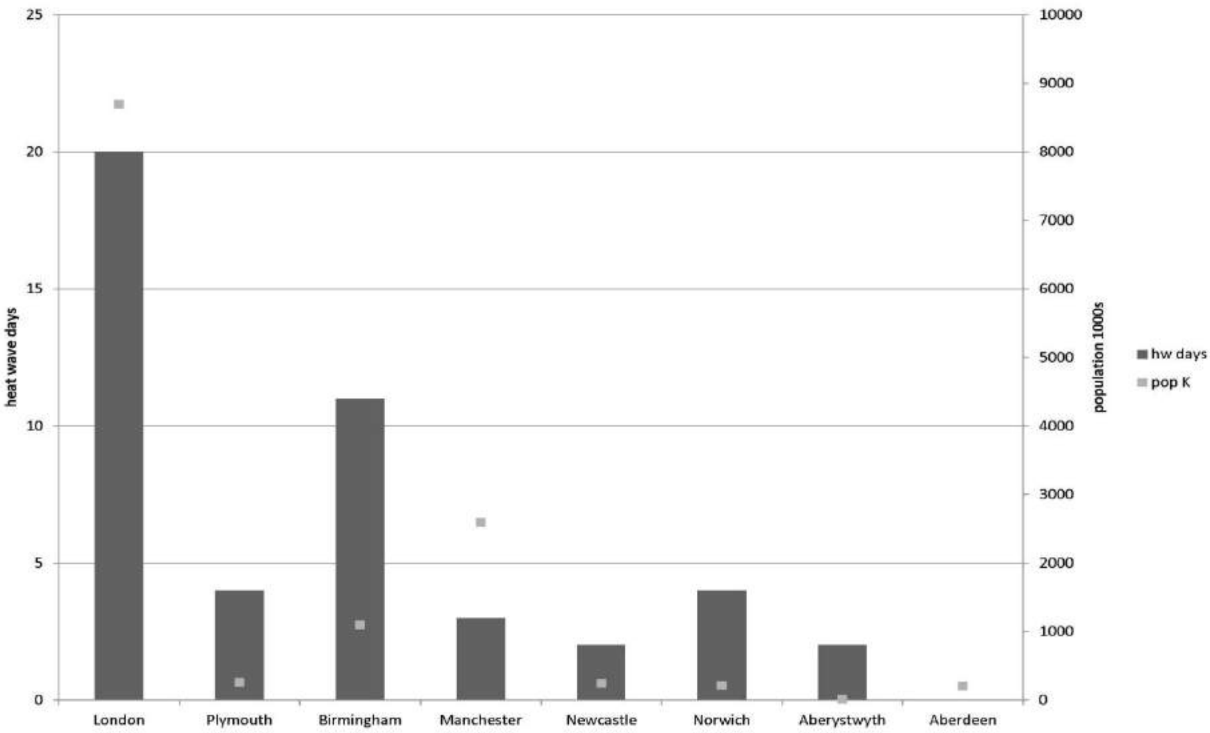


Figure 3. heat wave days and population of UK cities

The highest by some margin is London approximately double that of Birmingham in second place. The lowest is Aberdeen, which has no heat wave days as defined in the 2080 file. The quantification of heat wave days is not solely associated with the latitude of the city as Plymouth has less heat wave days than Birmingham. The link between heat wave events and population is unclear, with Manchester being more populated than Newcastle but not reflected in the heat wave days.

A large variation of the amount of heat wave events is shown, which globally is in the same ASHRAE climate zone and traditionally would be modelled with only two climate files, one for Scotland and one for England. The amount of heat wave days is not correlated with the population or the latitude of the cities.

Heat waves do not occur in the same time frame. At London they are mainly in August, at Plymouth in July, at Birmingham in August, at Manchester in August, at Newcastle between July and August, at Norwich in August and Aberystwyth in July. These clusters of dates are not random events and are different for different cities. This is not a simple translation error within the generated climate files. This matches previous findings in which a discrepancy within London city centre (Islington) and outskirt (Heathrow) was identified (Din and Brotas, 2016).

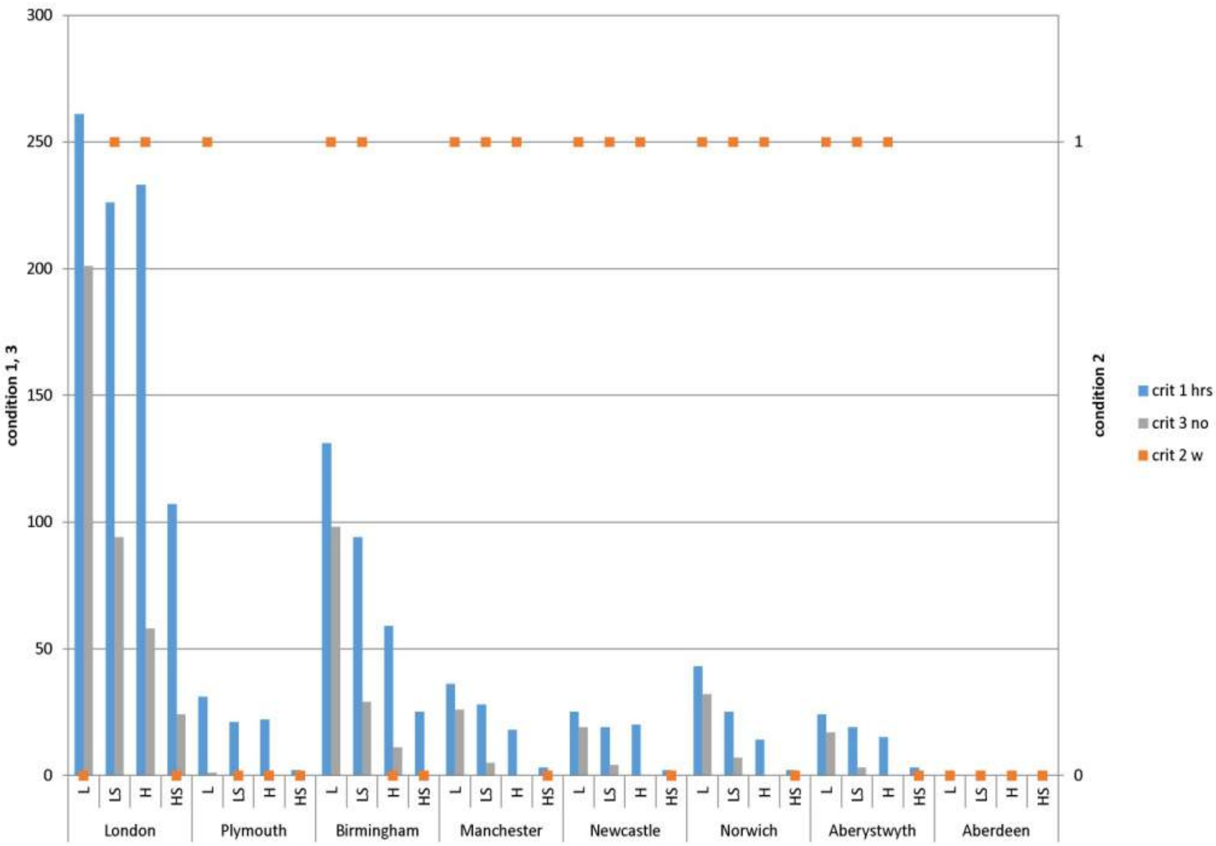


Figure 4. heat wave days and overheating events

Figure 4 shows a large variation in the amount of heat wave days and the effects that they bring to identical models placed within different UK cities. Again London is significantly higher than the second place, i.e. Birmingham. There is a trend however on how much each mitigation measure impacts on the amount of overheating experienced. Shading on a light weight construction results in a 25% drop in the amount of overheating hours (criterion 1) and about 50% more when considering heat stress events (criterion 3). This result is similar to those of a heavyweight construction in overheating hours in criterion 1. The most effective mitigation is experienced by a heavyweight construction and shading, which results in a 60% drop in overheating. It is worth mentioning that this is significantly less than the sum of the mitigation measures which would be greater than a 90% reduction of overheating under criterion 1 experienced.

The figures quoted above are not consistent across all UK cities and are largely based on the Birmingham results. A similar trend is seen for London but in lower count instances, in Newcastle the same conclusions cannot be made. Arguably only London and Birmingham require heat wave mitigation to take place, shading alone in Birmingham brings the number of overheating hours down to a similar level than the combined shading and thermal mass levels in London. The instances of Criterion 2 are of limited value in this analysis due to the short time periods involved.

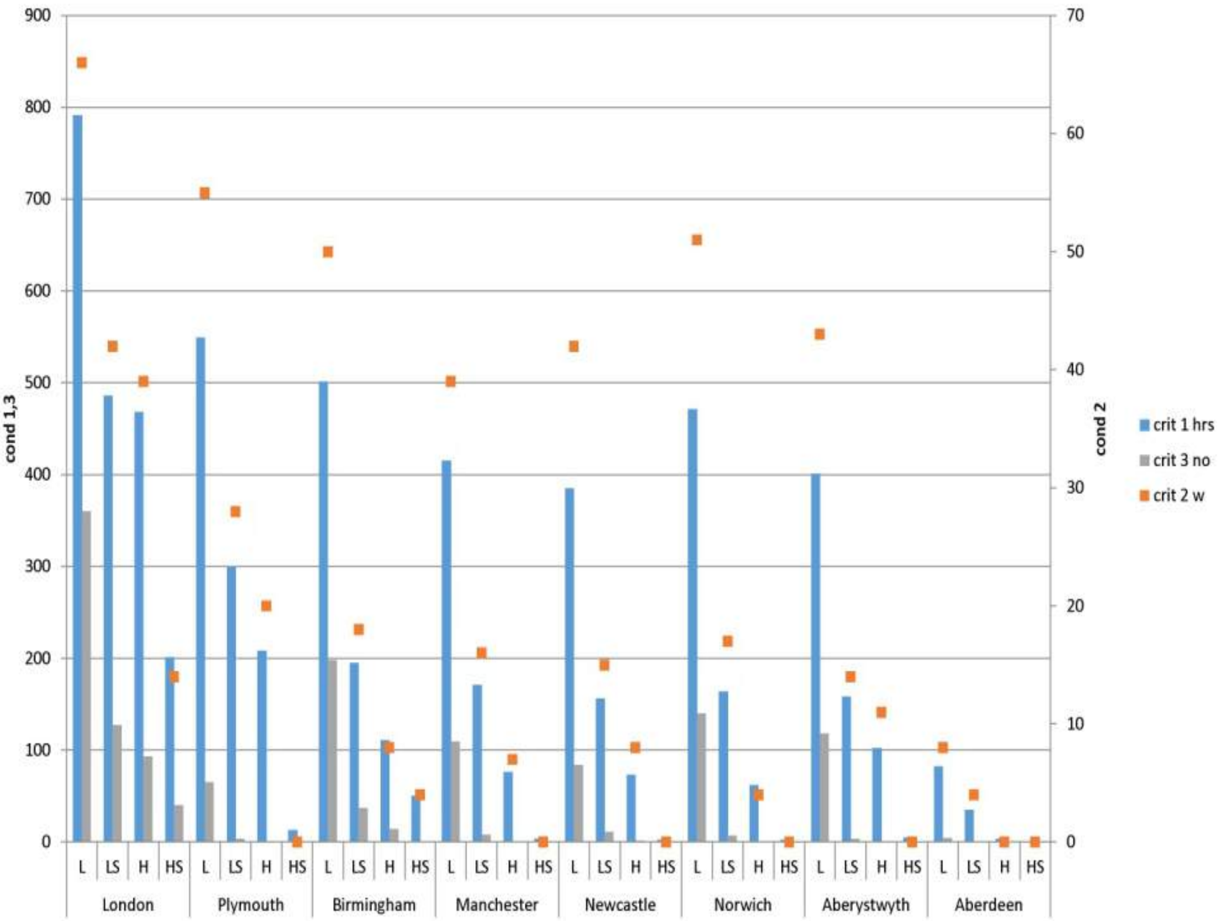


Figure 5. overheating events over the cooling season

Figure 5 shows the results over the whole cooling season as defined by TM52 for the same cities. Shading on a light weight construction results in a 60% reduction in criterion 1 overheating hours. Heavyweight construction results in 80% reduction in criterion 1 overheating hours and a combination of heavyweight and shading results in a 90% reduction in criterion 1 overheating hours. The trends for Criteria 2 and 3 show reductions with the addition of mitigation but again criterion 3 has the largest drop off and is significantly influenced by the addition of thermal mass.

The results for Plymouth and Norwich are significantly higher than those recorded from heat wave events which suggests that latitude has a higher influence over cooling season results. Uniform patterns are seen from the addition of mitigation apart from London which shows similar results for both shading on a lightweight construction and a heavyweight construction.

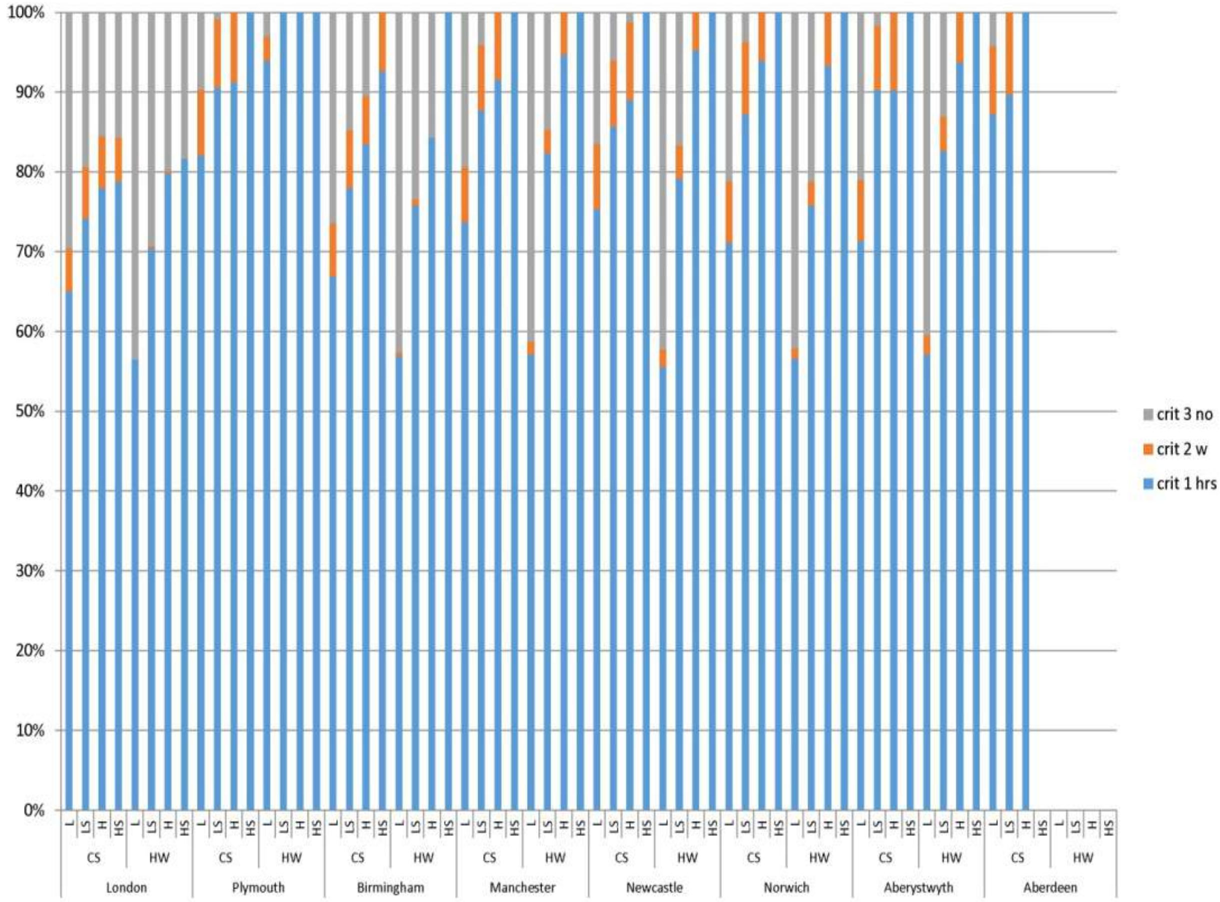


Figure 6. Proportion of TM52 criteria for both cooling season (CS) and heat wave (HW) events

Figure 6 presents all of the TM52 events combined. Although difficult to represent given the amount of models conducted Figure 6 shows that most results are dominated by the number of overheating hours (criterion 1) followed by criterion 3 and then criterion 2. With heat waves having short lasting effects, criterion 2 is not registered in most of the heat wave quantifications. As mitigation is applied the proportion of criterion 1 gets higher reinforcing previous graphs in which mitigation reduces the impact of heat stress events.

The impact of mitigation during heat wave events is more pronounced than that in a cooling season but this is largely a result of the number of instances recorded. Further trends should not be inferred by the graph which deals with proportions and not the quantification of the amount of overheating taking place.

6. Conclusions

Overall mitigation is effective in reducing the amount of overheating experienced in a modified TM52 technique. The inputs are in line with TM59 but are modified to give realistic results and not enhance them due to the additional loads imposed on the simulated rooms. Results from the heat wave and the whole cooling season should be dealt with separately as shading provides a 25% drop during heat wave events significantly lower than the up to 60% reduction during a cooling season. Thermal mass provides a 50% reduction during a heat wave compared to up to 80% during a whole cooling season. The combination of mitigation measures provides 60% reduction in heat waves rather than the 90% in a cooling season.

Thermal mass has to be planned at the start of the design process due to its structural implications in building design but shading can be placed as a retrofit option and provides significant results for south facing rooms.

In a heat wave the mechanism by which overheating occurs by the modified TM52 criteria is by criterion 1 with figures of 0 to 250 hours for UK cities in 2080. As demonstrated, criterion 2 is of limited use due to the short time periods allowing minimal quantification of daily weighted figure. Criterion 3 has a slightly lower range than condition 1 of 0 to 200 instances but when comparing back to the cooling season figures are 10 times higher than those experienced from the heat wave events.

Dealing with short term heat wave events has a similar approach to mitigating the thermal discomfort felt by occupants during a whole cooling season. The exercise has been useful in establishing the proportion heat wave effects contribute to the overall potential cooling season. The combination of thermal mass and shading provides the best mitigation against overheating. However, on a cost effective retrofit measure, solar shading provides the most cost effective mitigation solution. The qualification of results provides a method of comparison of differing periods of time although this cannot establish when overheating will occur as this requires a weighted mechanism as described in TM52. The models are internally compared and so are not influenced by the different inputs which result from TM59 approach.

7. Future implementation

The study provides a component towards a heat wave mitigation retrofit kit which could be issued in a cost effective way during heat wave events to reduce the number of heat stress and mortality events within existing buildings. To quantify the heat island effects within the weather files more real life surveys of the areas around the base weather stations whose files have been transformed is required to gain a greater level of certainty in calculating heat wave events. Further validation is required of the threshold temperatures used to define a heat wave event rather than the emergency service definition currently used in the UK. A further study is required to establish the impact of subsequent days in a heat wave period and its impact on the mitigation measures used rather than single days of heat wave effect.

A methodology is required to establish a probability from the calculations made such as first event 2035 with a one in 10 year return event to allow for future planning of these events on a risk basis.

8. References

ASHRAE, https://energyplus.net/weather, accessed 2018

Beizaee, A., Lomas, K.J., Firth, S.K., 2013. National survey of summertime temperatures and overheating risk in English homes. Building and Environment 65, 1–17. doi:10.1016/j.buildenv.2013.03.011

BRE, https://www.bre.co.uk/greenguide/podpage.jsp?id=2126, accessed 2018

BSi, 2007, Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, BS EN 15251:2007, British standards institute

Chen, L., Yu, B., Yang, F., Mayer, H., 2016. Intra-urban differences of mean radiant temperature in different urban settings in Shanghai and implications for heat stress under heat waves: A GIS-based approach. Energy and Buildings 130, 829–842. https://doi.org/10.1016/j.enbuild.2016.09.014

CIBSE, 2017. Design methodology for the risk assessment of homes. TM59. Chartered Institute of British Service Engineers

CIBSE Guide A Environmental design. 2016 Chartered Institute of British Service Engineers

CIBSE, 2013. The limits of thermal comfort: avoiding overheating in European buildings. TM52. Chartered Institute of British Service Engineers

DECC, 2012, The Government's Standard Assessment Procedure for Energy Rating of Dwellings, BRE press, 2012

Díaz, J., Carmona, R., Mirón, I.J., Ortiz, C., León, I., Linares, C., 2015. Geographical variation in relative risks associated with heat: Update of Spain's Heat Wave Prevention Plan. Environment International 85, 273–283. doi:10.1016/j.envint.2015.09.022

Din, A.U., Brotas, L., 2017. The Impacts of Overheating Mitigation within the Life Cycle Carbon of Dwellings Under UK Future Climate. Procedia Environmental Sciences, Sustainable synergies from Buildings to the Urban Scale 38, 836–843. https://doi.org/10.1016/j.proenv.2017.03.169

Din, A., Brotas, L., 2016. The evaluation of the variables of domestic overheating in the UK under TM52 using a future climate model- Guidance for designers. Proceedings of 9th Windsor Conference: Making Comfort Relevant, Cumberland Lodge, Windsor, UK, 7-10 April 2016. Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Eames, M., Kershaw, T., Coley, D.,2012. The appropriate spatial resolution of future weather files for building simulation. Journal of Building Performance Simulation vol5, Issue 6, DOI:10.1080/19401493.2011.608133

Hacker, J.N., De Saulles, T.P., Minson, A.J., Holmes, M.J.,2008. Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change. Energy and Buildings 40, 375–384. doi:10.1016/j.enbuild.2007.03.005

Henninger, R.H., Witte, M.J., 2014. EnergyPlus Testing with Building Thermal Envelope and Fabric Load Tests from ANSI/ASHRAE Standard 140-2011 EnergyPlus Version 8.2.0. US Dept of Energy

Hintz, M.J., Luederitz, C., Lang, D.J., von Wehrden, H., 2017. Facing the heat: A systematic literature review exploring the transferability of solutions to cope with urban heat waves. Urban Climate. https://doi.org/10.1016/j.uclim.2017.08.011

Jenkins, D.P., Ingram, V., Simpson, S.A., Patidar, S., 2013. Methods for assessing domestic overheating for future building regulation compliance. Energy Policy 56, 684–692. doi:10.1016/j.enpol.2013.01.030

Kim, K., Kim, B.S., Park, S., 2007. Analysis of design approaches to improve the comfort level of a small glazed-envelope building during summer. Solar Energy 81, 39–51. https://doi.org/10.1016/j.solener.2006.06.018

Lemonsu, A., Viguié, V., Daniel, M., Masson, V., 2015. Vulnerability to heat waves: Impact of urban expansion scenarios on urban heat island and heat stress in Paris (France). Urban Climate 14, Part 4, 586–605. doi:10.1016/j.uclim.2015.10.007

McLeod, R.S., Hopfe, C.J., Kwan, A., 2013. An investigation into future performance and overheating risks in Passivhaus dwellings. Building and Environment 70, 189–209. doi:10.1016/j.buildenv.2013.08.024

NHS, 2015. Heatwave plan for England, Public Health England, HMSO. London

Nobert, S., Pelling, M., 2017. What can adaptation to climate-related hazards tell us about the politics of time making? Exploring durations and temporal disjunctures through the 2013 London heat wave. Geoforum 85, 122–130. https://doi.org/10.1016/j.geoforum.2017.07.010

Passipedia, https://passipedia.org/, accessed 2018

Porritt, S.M., Cropper, P.C., Shao, L., Goodier, C.I., 2012. Ranking of interventions to reduce dwelling overheating during heat waves. Energy and Buildings, Cool Roofs, Cool Pavements, Cool Cities, and Cool World 55, 16–27. doi:10.1016/j.enbuild.2012.01.043

Salata, F., Golasi, I., Petitti, D., de Lieto Vollaro, E., Coppi, M., de Lieto Vollaro, A., 2017. Relating microclimate, human thermal comfort and health during heat waves: An analysis of heat island mitigation strategies through a case study in an urban outdoor environment. Sustainable Cities and Society 30, 79–96. https://doi.org/10.1016/j.scs.2017.01.006

Ward, K., Lauf, S., Kleinschmit, B., Endlicher, W., 2016. Heat waves and urban heat islands in Europe: A review of relevant drivers. Science of The Total Environment 569–570, 527–539. https://doi.org/10.1016/j.scitotenv.2016.06.119

Wolf, T., McGregor, G., 2013. The development of a heat wave vulnerability index for London, United Kingdom. Weather and Climate Extremes 1, 59–68. doi:10.1016/j.wace.2013.07.004

Zhang, K., Li, Y., Schwartz, J.D., O′Neill, M.S., 2014. What weather variables are important in predicting heat-related mortality? A new application of statistical learning methods. Environmental Research 132, 350–359. doi:10.1016/j.envres.2014.04.004

Zero Carbon Hub, 2012. Overheating in New Homes: A review of the evidence. NHBC Foundation. NF46. BRE Press. UK

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Overheating in UK homes: Adaptive opportunities, actions and barriers

Daniel L Wright[1], Victoria J Haines[2] and Kevin J Lomas[1]

[1] Building Energy Research Group, School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough, UK, d.wright@lboro.ac.uk;

[2] Loughborough Design School, Loughborough University, Loughborough, UK.

Abstract: New-build homes and bungalows are particularly at risk of overheating during hot UK summers. Bungalows are a dwelling type favoured by the elderly who are more vulnerable to the negative health impacts of overheating. Whilst modelling studies have identified overheating risk, monitored data is lacking and limited information about the adaptive opportunities available to households (e.g. ventilation and shading). Even less is known about the adaptive actions taken during hot spells or about the physical, physiological or psychological barriers to acting.

A mixed-method survey tool (OAST) was developed for this study and used to assess overheating occurrence, adaptive opportunities, actions taken and barriers to action. The tool was deployed with a cohort of new-build (n = 4) and bungalow homes (n = 4) in Loughborough, central England.

The survey highlighted potential indicators of overheating risk, including post-occupancy retrofit such as extensions and loft conversions. Occupants' reports provided context and were a key strength of the OAST. Expressed barriers to adaptive action included concerns about security, but there was an inherent lack of concern about overheating and the associated health risks. Recommendations are made for the further development of the OAST as a method of assessing overheating risk in households.

Keywords: Overheating, homes, monitoring, adaptive action, barriers

1. Introduction

There are concerns that as global temperatures increase due to climate change (Cook *et al.*, 2016), an increasing number of UK homes will suffer from summertime overheating (DEFRA, 2017). Homes built after 1990, as well as existing dwellings which will make up 80% of the housing stock in 2050 (RAE, 2010), are prone to overheating (Beizaee, Lomas and Firth, 2013; Lomas and Kane, 2013; Lomas and Porritt, 2017). The problems may be exacerbated if homes are retrofitted to reduce heating energy demands. While studies investigating the effect of design and physical construction on the risk of overheating continue to grow, there is still limited understanding of how people interact with their homes during warm periods, what might drive elected cooling actions, and what the barriers to such actions may be (Mavrogianni *et al.*, 2014).

By 2040, around 25% of the UK population is predicted to be aged over 65 (GOS, 2016; Age UK, 2017). The elderly are most at risk from the negative health impacts of overheating because of their physiological vulnerabilities (Kenney and Munce, 2003; Kovats, Johnson and Griffith, 2006; Vandentorren *et al.*, 2006; DCLG, 2012; Hajat *et al.*, 2014; PHE, 2015; Vardoulakis *et al.*, 2015; Dengel *et al.*, 2016; Lomas and Porritt, 2017). Modelling studies have identified bungalows, a style traditionally preferred by older people, amongst the properties at risk of overheating. This corroborates research by Vandentorren et al. (2006) who concluded that one of the housing characteristics associated with heat-related morbidity was "sleeping on the top-floor, right under the roof" (2006, p. 1), a feature shared by both bungalows and top-floor flats. At present, there is limited evidence from monitoring of bungalows (Vellei *et al.*, 2017) to support these assertions, thus further investigation is essential for better understanding the experiences of bungalow occupants, their responses to high temperatures, and the factors that may constrain the actions they take to reduce the risks to their health.

The absence of mechanisms by which internal temperatures might be lowered, termed *adaptive opportunities*, or limited understanding of how to mitigate elevated temperatures increase the risk to health from high temperatures (Vardoulakis *et al.*, 2015). Recognition of the opportunities for cooling could be integral to an occupant's conceivable adaptive strategies; however, many factors may contribute to what strategies are chosen, which are avoided, and even which might not be identified at all. The adaptive opportunities available may be reduced through dwelling refurbishment. For example, when windows are replaced, the number, and security, of opening windows is often reduced, extensions increase the plan depth, and conservatories block access to outside air. The effects of these changes are exacerbated by higher levels of insulation, which reduces heat loss through the fabric, and reduced background infiltration (Dengel *et al.*, 2016).

The actions that an occupant takes to regulate temperature are termed *adaptive actions*. In free-running dwellings, windows are a key means of reducing indoor air temperature (Nicol, 2001), but utility is dependent on effective use (Palmer *et al.*, 2016). It is recommended that occupants take advantage of cooler night air by opening windows to reduce the temperature of their home (PHE, 2015). Night ventilation requires forward planning which is more difficult for those with cognitive impairment, a condition that is more common amongst the elderly (Lomas and Porritt, 2017). Security risks may also mean that night ventilation is not feasible for those living in bungalows and ground floor flats (Dengel and Swainson, 2012; Mavrogianni *et al.*, 2017; McLeod and Swainson, 2017), and it is likely that a disproportionately high number of elderly people live in ground floor flats and bungalows, the very dwelling type that is most at risk of overheating.

The research reported in this paper sought to understand the incidence of overheating, the factors that were causing it and the actions taken by occupants, why these particular actions were chosen and any barriers to action. In short, the research objectives were designed to further three lines of enquiry 'what can occupants do?', 'what do occupants do?', and 'what do occupants not do and why?'.

Temperatures were monitored during the summer of 2017 in a sample of four new houses and four bungalows in Loughborough in the English Midlands. They included four dwellings occupied by people over 60. The monitored temperatures were assessed against the static overheating criteria defined by the UK Chartered Institution of Building Services Engineers (CIBSE, 2006) and the World Health Organisation (WHO, 1991) as well as the CIBSE adaptive criteria (CIBSE, 2013). A physical survey, to identify the adaptive opportunities, and a semi-structured interview, to understand adaptive actions and barriers, were also undertaken. A new survey instrument was developed for this purpose, the Overheating Adaptive Opportunities, Actions and Barriers Survey Tool (OAST), which is freely available (Wright *et al.*, 2018).

2. Sampling and cohort recruitment

Non-probability convenience and purposive sampling strategies were utilised for recruitment of households because the focus was on developing in-depth home profiles rather than the generalisability of results. The households in the research (n = 8) occupied four post-1990 new build houses, which were recruited from Loughborough University staff, and four bungalows recruited through postal and email advertisements. Eligibility criteria for involvement in the study included a requirement that participants had resided in their home for at least two years and lived in the UK for at least five years. Eleven interviewees from the eight households took part in semi-structured interviews, of which five participants were aged between 61 and 83 (Table 1).

Table 1. Characteristics of each dwelling, the occupants and reported overheating

Case	Type	Total no. of occu-pants	Gender(s) and age(s) of respondent(s)	Occupancy[1]	Tenure	Overheating reported?	Typical Heating Start (month)	Typical Heating End (month)
N01	New Build	2	M (64)	Home/varied	Owner	Yes Utility room	Oct	May
N02	New Build	1	M (30)	Partial/regular	Owner	No	Oct	Apr
N03	New Build	3	M (38) & M (30)	Home/varied	Tenant	No	Oct	May
N04[2]	New Build	2	M (51)	Partial/varied	Owner	No	Oct	May
B01	Bungalow	1	M (70)	Home/varied	Owner	Yes Conservatory	Oct	Apr
B02	Bungalow	2	M (61) & F (62)	Home/varied	Owner	Yes Dining room Main bedroom	Oct	Mar
B03	Bungalow	1	M (83)	Home/regular	Owner	Yes Conservatory	← All Year →	
B04	Bungalow	2	M (41) & F (40)	Partial/varied	Owner	Yes Living room Kitchen Spare bedroom	Sep	Apr

[1] Occupancy was categorised in the following way: Partial/regular = Weekdays approx. 08:30-18:00 all away from home | Partial/varied = Weekdays away from home daily but not fixed times | Home/regular = Regular pattern of up to half-a-day away from home | Home/varied = Irregular pattern of up to half-a-day away from home (Baborska-Narożny, Stevenson and Grudzińska, 2017).

[2] House N04 was not monitored during the hot weather period and data collected are not analysed in this paper.

Nine of the eleven interviewees were male and all homes were owner-occupied except for one (N03). No significant difference ($p = 0.11$) was found between the mean average age of respondents living in new build homes (42) and those in bungalows (60). Occupant ages ranged between 30 and 83 and three households were inhabited by just one person for most of the time (N02, B01 and B03).

3. Methodology

A mixed-methods approach was elected to explore the three research questions (reinterpreted in Table 2). Data collection took place between June and August 2017, and was split across three phases of approximately one month each (Table 3). The surveys were all completed on the initial home visit, and necessary secondary data sources, such as digital maps, accessed after each visit.

Table 2. The research questions and the qualitative and quantitative methods used to investigate each one

Research Question	Methods of investigation
1. What are the designed opportunities for, and barriers to, mitigating elevated indoor temperatures that can be evaluated with a physical assessment?	Building and glazing survey using to create floor plans and layout window schematics to evaluate designed adaptive opportunities and possible barriers to utilisation.
	Dry-bulb temperature monitoring to investigate instances of overheating.
2. How do occupants utilise adaptive opportunities to cool their home in uncomfortably elevated temperatures and what strategies do they utilise?	Semi-structured interview with questions focused on identifying steps taken to cool the dwelling.
	Dry-bulb temperature monitoring to assess impact of actions.
3. What might be the perceived barriers that prevent occupants from utilising opportunities to cool their home?	Semi-structured interview with questions around possible factors that might prevent occupants using a ventilation strategy.

The installations of temperature sensors were staggered across the months of June and July depending on the timing of the home visit. Sensors were placed in the main bedroom and the living room in each household, consistent with previous research (McGill *et al.*, 2016; Baborska-Narożny, Stevenson and Grudzińska, 2017; Gupta, Barnfield and Gregg, 2017; Mavrogianni *et al.*, 2017; Morgan *et al.*, 2017; Symonds *et al.*, 2017; Vellei *et al.*, 2017). Instead of monitoring the designed living room and main bedroom, the functional living room and main bedroom were selected to get a better insight into experienced indoor temperatures. Semi-structured interviews were conducted on both the initial and follow-up home visits. All interviews were recorded digitally, and hand-written notes were made during each interview.

Table 3. Overview of socio-technical procedure for gathering data

Phase One Initial visit (Jun-Jul)	**Phase Two** Intermediate visit (Jun-Aug)	**Phase Three** Follow-up visit (Jul-Aug)
• Interview one • Building and glazing survey	• Temperature monitoring	• Interview two

3.1. The OAST: Physical survey

Data related to the design, layout and features of each participating household as well was occupant experiences and interpretations around the topic of overheating were gathered methodically using the Overheating Adaptive Opportunities, Actions and Barriers Survey Tool (OAST), which was developed specifically for this research (Wright et al., 2018). The items included in the OAST were compiled from the Energy Use Follow-Up Survey (Hulme, Beaumont and Summers, 2013), the English Housing Survey (DCLG, 2015), DEFRA nuisance smells guidance (DEFRA, 2015) and the AECOM guidance for typical noise levels and subjective evaluation (AECOM, 2010) as well as other study-specific items (Table 4).

Detailed schematics of windows and glazed doors (such as patio doors) were recorded. Using the OAST, measurements were taken to be able to calculate the total area, the glazed area, and the operable area (Figure 1). Additionally, windows and doors were surveyed to record: orientation, presence of background ventilation (e.g. trickle vents), opening mode (e.g. casement), presence of blinds or curtains, fixture specifications, glazing type, and security.

Table 4. A summary of data collected using the OAST and means of collection.

Aspect	Element	Measurement method
Geographical, meteorological and situational dwelling data	Proximity of the dwelling to other structures	Secondary data
	Orientation of the designed main façade	Secondary data
	Weather at time of interview	On-site observation
	Distance from a pubic road	Observation
	Shading sources	4-point percentage shading scale
	Possible sources of noise	8-point Likert scale
	Possible sources of smell	8-point Likert scale
Building fabric	Internal structure	Occupant response and observation
	Insulation installed	Occupant response and observation
	Roof type	Secondary data and observation
	Construction date	Occupant response and secondary data
	Heating system	Occupant response and observation
Occupancy details	Duration of occupancy	Occupant response
	Tenure	Occupant response
	Number of occupants	Occupant response
Building use	Frequency of window use	Occupant response
	Typical heating months	Occupant response
Room properties	Ventilation opportunities (passive and active)	Observation
	Room dimensions	Measurement
	Presence of heat generating appliances	Observation
	Floor type	Observation
	Internal door floor clearance	Measurement
Glazing schematics	Aperture area	Measurement
	Free area	Measurement
	Fixture type	Observation
	Blinds	Observation
	Curtains	Observation
	Background ventilator status and dimensions	Observation and measurement
	Security measures (locks)	Observation

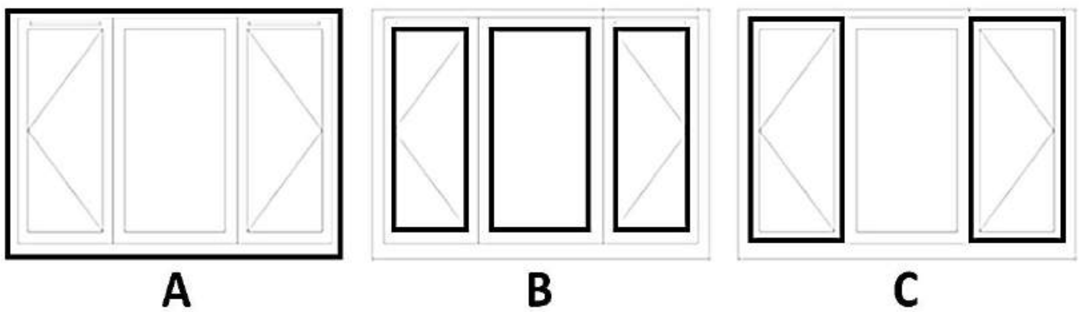


Figure 1. Window and glazed/semi-glazed door details captured in the OAST: total area (A); glazed area (B); and operable area (C)

3.2. The OAST: Monitoring

Taking into consideration the CIBSE TM52 criteria for defining overheating in free-running buildings (CIBSE, 2013), between two and five calibrated Onset HOBO temperature data sensors (UA-001-08 and higher capacity UA-001-64 models) were deployed in each household to log room temperatures from midnight the day after the initial visit (Figure 2). Ten-minute logging intervals were chosen to enable direct comparison with data collected by the weather station located at Loughborough University whilst not overloading the storage capacity of the loggers.

In dwelling N03, data from Secure SES humidity and temperature (reported margin of error ±0.5°C) sensors, which were installed in May 2017 as part of a parallel research project, were utilised to extend the number of days of data. Dwelling N04 was monitored between 5 July and 5 August, but the data are not included in the analysis because the period has limited overlap with data collected in the other dwellings.

Figure 2. Preparing the Onset HOBO temperature data sensors (UA-001-08 and UA-001-64 models)

3.3. OAST: Occupant interviews

A flexible structure was outlined for the interviews to help the conversation to flow naturally (Gray, 2004). The interview topics were focused on investigating the three research objectives. However, the review of literature revealed the importance of including specific prompts to probe topics of interest, for example asking about awareness of temperature control best practice (Baborska-Narożny, Stevenson, & Grudzińska, 2017), about sources of information for combatting overheating (Lomas and Porritt, 2017), and about recognising opportunities for cooling (Meinke *et al.*, 2017).

4. Results

4.1. Incidence of overheating

The UK Met Office heatwave thresholds[1] were not met during the monitoring period (Met Office, 2017). However, between the 16th and the 23rd of June 2017, the average night-time (22:00-07:00) threshold of 15°C for the East Midlands region was exceeded on six consecutive days (Figure 3). As such, this period is called herein a *hot spell*, as opposed to a heatwave. Temperatures monitored during this eight-day period are analysed here. However, sensors had not been located in house N04 by the start of the hot spell, so only the data from the other seven households are analysed.

[1] The UK heatwave thresholds vary by region; the average threshold temperature is 30°C during the day and 15°C overnight.

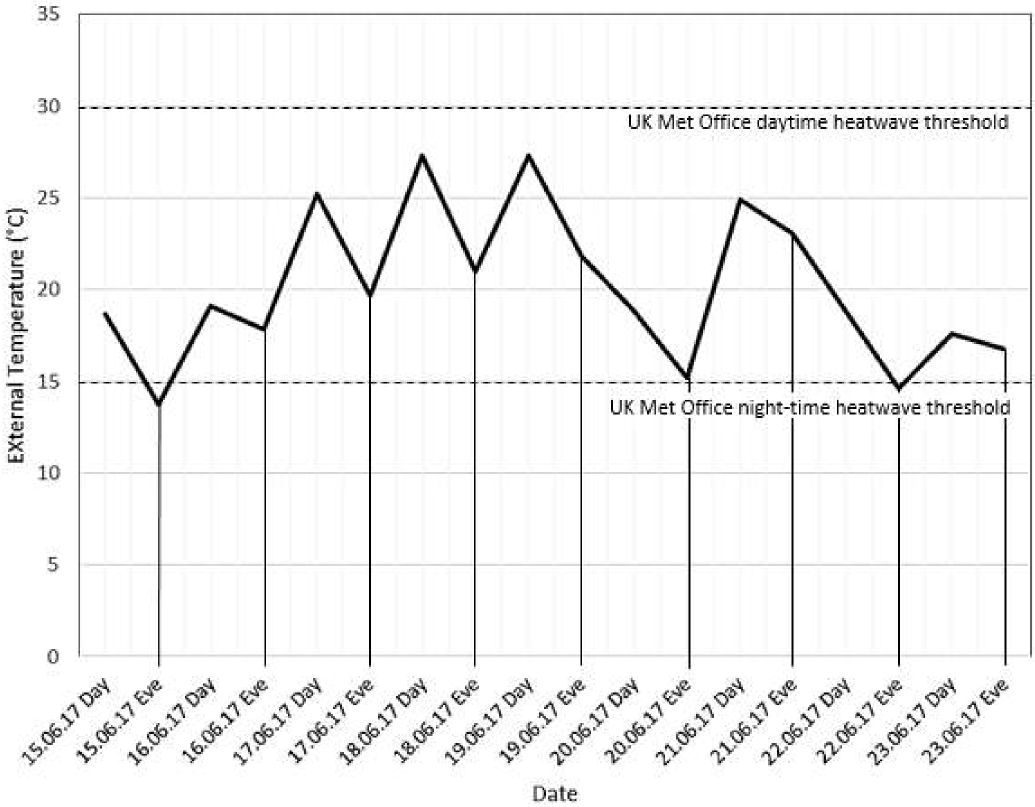


Figure 3. Average daytime (07:00-22:00) and night-time (22:00-07:00) temperatures between 22:00 on the 15th of June 2017 and 07:00 on the 24th of June 2017.

Measured indoor temperatures were collated and processed to calculate temperature exceedance metrics, considering both static (Table 5 and Table 6) and adaptive overheating criteria (Figure 4, Figure 5 and Table 7). Exposure to temperatures above 24°C is considered to be potentially unhealthy (WHO, 1991).

The CIBSE Guide A (CIBSE, 2006) places a 1% limit on the allowable annual exceedance of 28°C in living rooms during occupied hours. In this work the 28°C/1% criterion was applied to the functional living rooms, with occupied hours considered to be all the non-sleeping hours (i.e. 07:00 to 22:00), which is in line with the recently published CIBSE Technical Memorandum (TM) 59 (CIBSE, 2017). Overheating was deemed unacceptable if 28°C was surpassed for more than 54 hours, which is approximately 1% of total annual hours. The same Guide places an annual 26°C/1% limit on bedroom temperatures, a limit which is retained in TM59. For bedrooms occupied from 22:00 to 07:00, this equates to 33 hours annually.

No significant difference was discovered between the mean, maximum and minimum temperatures monitored in the new builds and bungalows (Table 5). During the eight-day hot spell, temperatures during the daytime exceeded 24°C in the functional living rooms for between 62% and 99% of hours. The functional living room in bungalow B03, which was a conservatory, was overheated most of the time, exceeding 28°C for 79% of the daytime hours (i.e. for 89 hours). This space would be considered as overheating by the CIBSE 28°C/1% criterion even if the temperature never exceeded 28°C during the rest of the year. The living rooms of three other dwellings (B01, N03 and N03) exceeded 28°C for between 2% and 11% of daytime hours during the hot spell.

Table 5. Indoor temperatures monitored in the living room during daytime hours (07:00-22:00) between 07:00 on the 16th of June and 22:00 on the 23rd of June 2017.

Case	Room	Temperature (°C) Mean	Max	Min	No. of Hours… > 24°C	> 28°C	% of Hours… > 24°C	> 28°C
N01	Living	26.0	28.9	23.5	99	13	88	***11***
N02	Living	24.7	26.4	22.8	82	0	73	0
N03	Living	25.1	28.7	22.4	85	8	75	***7***
B01	Living	24.6	28.1	22.1	80	2	71	***2***
B02	Living	24.3	28.0	21.6	70	0	62	0
B03	Living*	34.0	58.9	23.7	112	89	99	***79***
B04	Living	24.7	27.8	22.6	78	0	69	0

* The functional living room in B03 was the designed conservatory
Italicised bold indicates failing the CIBSE 28°C/1% limit for the functional living room during the hot spell
Shading indicates failing the CIBSE 28°C/1% threshold for annual overheating hours in the functional living rooms

There was no significant difference between the average main bedroom night-time exceedance hours in the new-build housed or bungalows. Temperatures exceeding 26°C were recorded in the main bedroom of house B03 for 52 hours (Table 6). This is equivalent to 64% of night-time hours over the hot spell, or 1.6% of annual night-time hours, thus indicating that the overheating risk is unacceptably high, even if the temperature never exceeds 26°C during the rest of the year. The second warmest main bedroom, B02, exceeded 26°C for 40% of night-time hours (32 hours total) over the hot spell, equating to 0.97% of annual night-time hours (Table 6).

Table 6. Indoor temperatures monitored in the main bedroom across night-time hours (22:00 and 07:00) between on 22:00 on 15th of June 2017 and 07:00 on 24th of June 2017.

Case	Room	Temperature (°C) Mean	Max	Min	No. of Hours… > 24°C	> 26°C	% of Hours… > 24°C	> 26°C
N01*	Main Bed	-	-	-	-	-	-	-
N02	Main Bed	24.7	27.5	22.8	49	15	60	***19***
N03	Main Bed	24.5	27.9	20.9	48	19	59	***24***
B01	Main Bed	24.6	28.4	21.5	51	20	64	***25***
B02	Main Bed	24.6	32.4	19.0	48	32	60	***40***
B03	Main Bed	26.8	29.8	24.7	81	52	100	***64***
B04	Main Bed	24.4	27.5	22.7	41	11	51	***14***

* The N01 main bedroom sensor failed before the warm spell
Italicised bold indicates failing the CIBSE 26°C/1% limit for the main bedroom during the hot spell
Shading indicates failing the CIBSE 26°C/1% threshold for annual overheating hours in the main bedroom

The adaptive criteria for assessing overheating in naturally ventilated homes, which are defined in CIBSE TM52 (CIBSE, 2013), and retained for living rooms in TM59 (CIBSE, 2017), follow the approach set out in the International Standard BSEN15251 (BSI, 2007). Envelopes of acceptable temperatures, defined by upper and lower thresholds, are set which increase with the running mean of the average daily ambient temperature (Figure 4). The envelopes have different widths applicable to different categories of persons. Cat I, the narrowest band, is applicable to very sensitive and fragile persons with special needs, and thus seems appropriate for assessing the risks of overheating for elderly people (households N01, B02 and B03), Cat III, which is appropriate for existing buildings, was adopted for the other households.

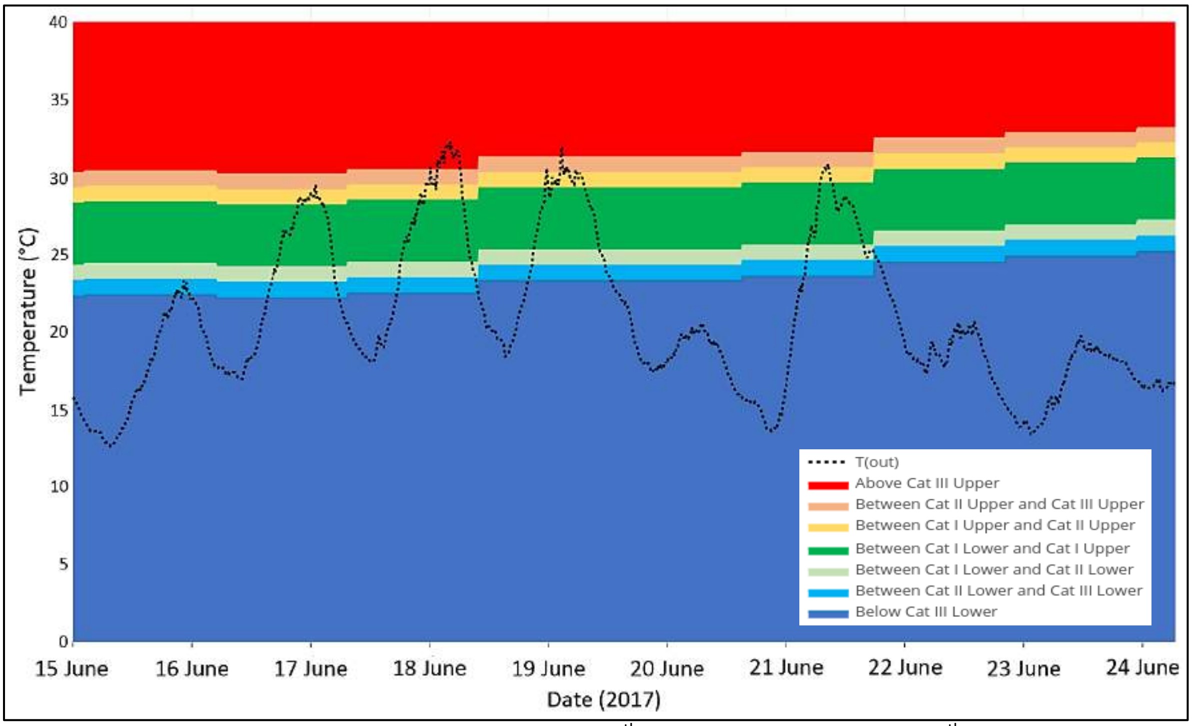


Figure 4. Ambient temperature between 22:00 on the 15th of June and 07:00 on the 24th of June 2017 and the BSEN15251 thresholds for Cat I, II and III.

The percentage of hours during the monitoring period for which daytime and night-time temperatures were within each category envelope are shown in Figures 5 and 6. It is clear that both spaces in the majority of homes were within the Cat I comfort envelope or cooler, suggesting that they were not uncomfortably warm.

The overheating risk in the rooms was assessed using the first of the CIBSE TM52 criteria. This sets a limit of 3% on the number of occupied hours between the 1st of May to the 30th of September for which the operative temperature may exceed the upper category threshold by 1K or more. Here the measured room temperatures were used in place of true operative temperatures.

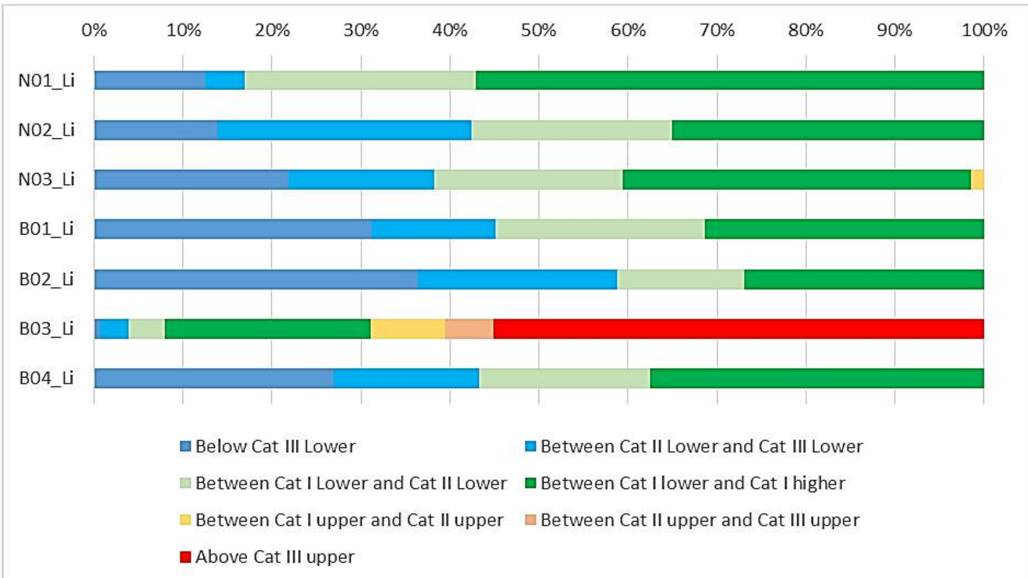


Figure 5. Percentage of time between 07:00 and 22:00 that the temperatures in the functional living rooms lay within the Cat I, II and III envelopes between 07:00 on the 16th of June and 22:00 on the 23rd of June 2017.

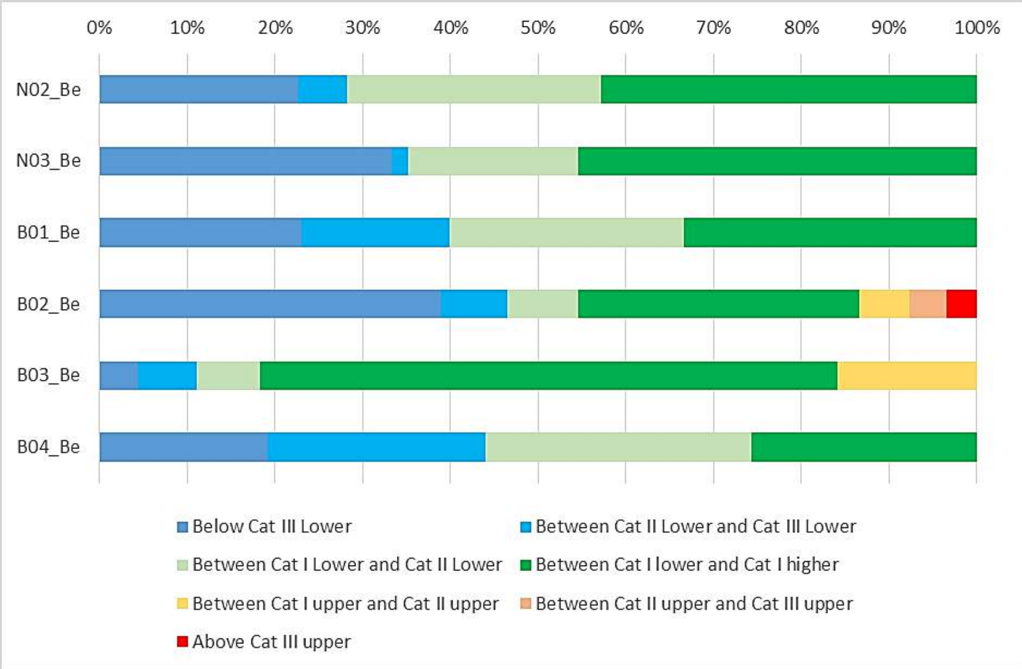


Figure 6. Percentage of time between 22:00 and 07:00 that the temperatures in the main bed rooms lay within the Cat I, II and III envelopes between 22:00 on the 15th of June and 07:00 on the 24th of June 2017.

For the assumed day and night-time occupancy, 3% equates to 3 hours during the hot spell for main bedrooms, 99 hours annually, and 4 hours during the hot spell for the functional living rooms, 164 hours annually. An assessment of monitored temperatures found that, as expected, the functional living room in bungalow B03 (the conservatory) far exceeded the 3% limit during the hot spell, with 72% of hours exceeding the Cat I upper threshold (Figure 5, Table 7). The temperatures in the remaining spaces never exceeded either the Cat I or the Cat II upper thresholds by more than 1K.

Table 7. The daytime hours for which the indoor temperature exceeded the adaptive standard upper threshold by at least 1K in the functional living rooms between 07:00 on the 16th of June and 22:00 on the 23rd of June 2017.

Case	Room	No. of hours above...			% of hours above...		
		Cat I	Cat II	Cat III	Cat I	Cat II	Cat III
N01	Living Room	***0***	0	0	***0***	0	0
N02	Living Room	0	0	0	0	0	0
N03	Living Room	0	0	0	0	0	0
B01	Living Room	***0***	0	0	***0***	0	0
B02	Living Room	***0***	0	0	***0***	0	0
B03	Living Room*	***87***	80	71	***72***	67	59
B04	Living Room	0	0	0	0	0	0

* The functional living room in B03 was a conservatory
Shading indicates a fail at the CIBSE 3% adaptive upper threshold was exceeded by >1K
Italicised bold indicates applicable figure as home occupied by elderly people.

The main bedroom in B02 was also deemed to suffer from overheating, with 12% of available hours exceeding the Category I threshold (Table 8).

Table 8. The daytime hours for which the indoor temperature exceeded the adaptive standard upper threshold by at least 1K in the bedrooms between 22:00 on the 15th of June and 07:00 on the 24th of June 2017.

		No. of hours over…			% of hours over…		
Case	Room	Cat I	Cat II	Cat III	Cat I	Cat II	Cat III
N01	Main Bed**	-	-	-	-	-	-
N02	Main Bed	0	0	0	0	0	0
N03	Main Bed	0	0	0	0	0	0
B01	Main Bed	***2***	0	0	***1***	0	0
B02	Main Bed	***9***	4	1	***12***	5	2
B03	Main Bed	***2***	0	0	***2***	0	0
B04	Main Bed	0	0	0	0	0	0

** The N01 Main bedroom sensor failed before the warm spell
Shading indicates a fail at the CIBSE 3%/adaptive upper threshold exceeded by >1K
Italicised bold indicates applicable figure as home occupied by elderly people.

Bungalows B02 and B03 were both occupied by retirees, the Cat I threshold is therefore relevant. The failures against the TM52 criterion suggest that these elderly persons are at more risk of experiencing uncomfortably high indoor temperatures in the summer than the other householders in the cohort. This is particularly concerning given that high temperatures pose a greater risk to health for elderly people.

4.2. Adaptive opportunities

Windows in the dwellings admit sunlight leading to solar gain and so contribute to any overheating risk, but the operable areas within each window, as well as external doors, provide the main opportunity for ventilation cooling. Overall, the bungalows were much more highly glazed than the houses, having glazing-to-floor area ratios between 14% and 32%, compared to 9% to 15% for the houses. The relative area of operable windows and doors in the two dwelling types was, however, similar: 7% to 12% for the bungalows, and 8% to 12% for the houses. If the external doors are excluded, on the grounds that opening them would create an unacceptable security risk, the relative operable areas become: bungalows, 5% to 7%; and houses, 7% to 9%. (The average floor area of the two types of dwelling was similar: 116m^2 for the bungalows and 103m^2 for the houses.) These figures suggest that the bungalows are likely to experience greater summertime solar gains than the houses, yet provide only the same, or less, ventilation opportunity.

To examine the relationship between the incidence of overheating and the solar gain and ventilation opportunities in the functional living rooms and the bedrooms, the glazing-to-floor area ratios (Gla:Flo) and operable area-to-floor area ratios (Ope:Flo) were calculated (Figures 8a and 8b). The very high relative area of glazing (47% of floor area) yet much lower operable area (12% of floor area), in the living room of bungalow B03, may well explain the overheating that was observed (Figure 5 and Table 7). House N03 also has a high glazed area but low, 4%, operable area (cf. Figure 5). The overheating in the bedroom of bungalow B02 may also be due to the high relative glazed area (21%) but limited operable area (4%).

The windows in bedrooms B01 and B03 actually faced onto conservatories (e.g. Figure 9), and so the opportunity to ventilate these two spaces with external air was very limited indeed.

In newly built houses, trickle vents provide background ventilation, and were present in the windows and patio doors of all the houses surveyed, there were no trickle vents in the bungalows. Trickle vents provide limited ventilation cooling capability however. The utilisation of designed opportunities for cooling was explored further through the semi-structured interviews that were part of the OAST.

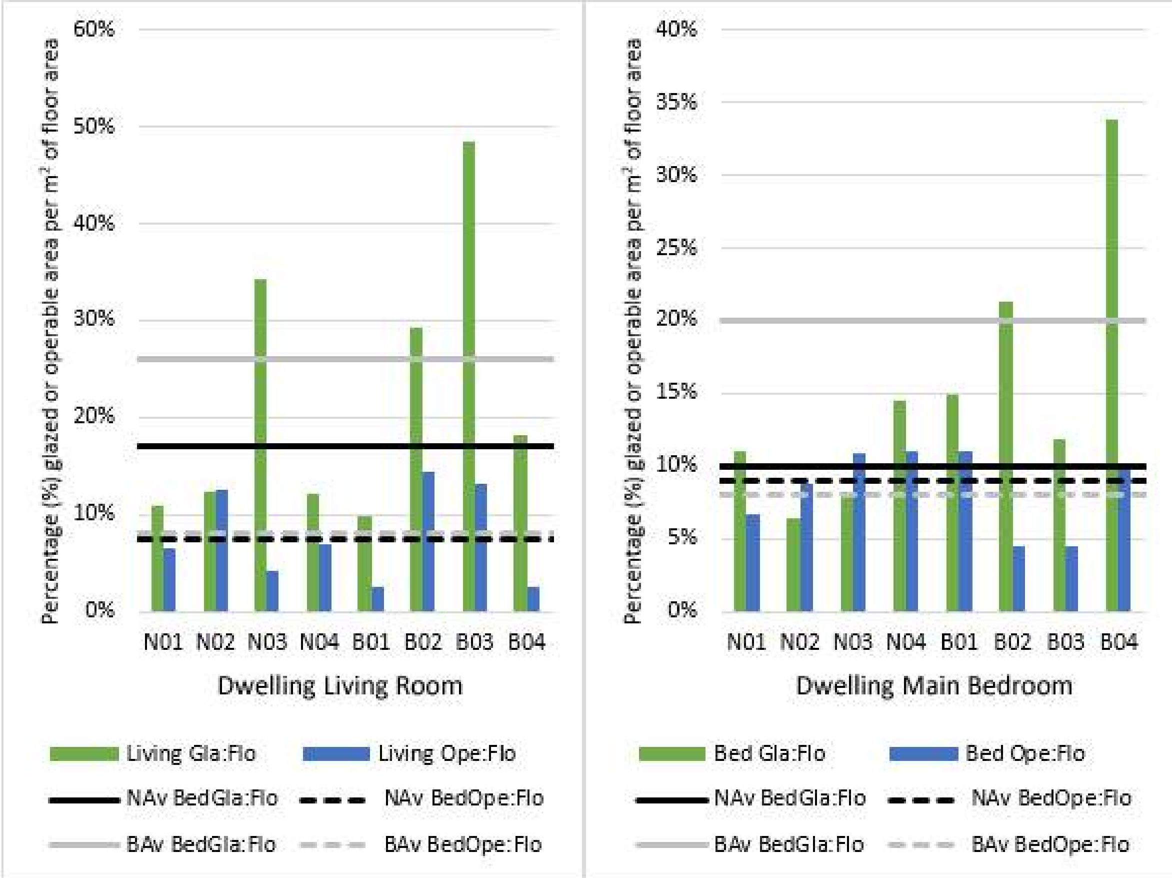


Figure 7. Comparison of the relative glazed (Gla:Flo) areas and relative operable window areas (Ope:Flo), in the functional living rooms and main bedrooms of each bungalow and house

Figure 8. The main bedroom window in bungalow B03 faces directly into the conservatory, which acted as the functional living room.

4.3. Occupant interviews about overheating

In the semi-structured interviews, all the bungalow respondents reported overheating. In contrast, uncomfortably elevated temperatures were only reported for one new house (N01). The interview respondents from houses (N02 and N03) were considered experts in the control of indoor temperature and so were perhaps better placed to achieve a comfortable indoor environment. The interviews with the households living in homes that suffered from overheating are of particular interest, as they shed light on their experiences and the actions they take to try to stay cool.

For the couple living in bungalow B02, the overheating in the main bedroom meant "*sleeping is trickier*". Their bedroom was located in the partially converted loft, which had south-west facing glazing with limited operable area and was equipped with an electric fan. During the day, the windows were the primary means of keeping the bedroom cool, however, when they "*weren't in and* [they] *weren't able to leave the windows wide open*" perceived temperatures were "*up to mid-30s*". If the temperatures were uncomfortably high while trying to sleep, "*the window gets thrown wide open and the duvet gets thrown off*". Rather than using the fan if it was too hot, they would "*probably just move"* to an alternative room such as "*the front bedroom where it's much cooler*". They remarked that they were "*both a bit skinny*" to use the fan, alluding to the uncomfortable breeze that it created. The occupants of house N01 overcame their fan's chilling effect by using "*a very thin cotton cloth for when it's too hot to have the duvet cover over the top …… just enough to keep the breeze off"*.

The adaptation of moving to a cooler location, even at night, is an opportunity limited to households with sufficient space. The literature recognises that overcrowding in homes is linked to higher internal gains and increased risk of overheating (Vellei *et al.*, 2017), and could also mean a reduction in adaptive opportunities for occupants.

Bungalow B03 was occupied by an elderly man. He considered his conservatory to be "*the ideal room to be in when the sun is shining"* and he would spend most of his time in it whilst at home. Upon experiencing uncomfortably high temperatures, the first thing he would do was to "*make sure the heating's off*". Two of the other households (B02 and N03) also sought to reduce sources of heat as their first action, for example, by turning off electrical appliances.

Getting "*as many windows open as possible*" was a common response to uncomfortably high temperatures for all the households interviewed, however, only two households used a specific premeditated ventilation strategy to maximise cooling. One of the occupants in bungalow B04 noted that, *"if it gets really hot, we open the front door, because then you get a nice through-draft. I think it's made a big difference."* Whilst premeditated, this is still a reactive tactic in response to elevated indoor temperatures, rather than a forward-thinking tactic designed to prevent overheating in the first place.

4.4. Barriers to actions

In every discussion around the use of windows, security was raised as a reason to not utilise the adaptive opportunity they afforded. For example, the elderly occupant of bungalow B01 was "*always concerned about somebody coming in… with it being a bungalow… I don't know if they could get in through the windows as they are, as they're quite small gaps, but you always wonder… I'd like windows open through the night, but I'm reluctant to leave an open window when I'm out… I don't like to do it in the day*." Likewise, the elderly occupant of bungalow B03 reported that he "*always* [closed] *the door* [in the conservatory] *and that's for security reasons*". However, concerns about safety and security were not restricted to elderly bungalow occupants, for example the young man that occupied house N02 rarely left open the kitchen window open, which would have been useful for creating a through-draft, because, "*somebody can get inside through the kitchen window if I leave it open because it's at a low level... I don't feel safe leaving it open and sitting* [in the living room] *or upstairs.*" For the man in bungalow B01, security fears meant that "*unless if it's very hot, I tend not to open the windows, because there's always the danger that you go out and forget that they're open… So, I tend to err on the side of caution and not open them*."

Insect pests were cited by four households as a reason why they might be reluctant to open a window for cooling, particularly at night. For example, the young man in house N02, noted "*when it's warm and I'm sleeping in the bedroom and I would like to keep the window open… sometimes I get flies and mosquitos and stuff… so I tend not to open the window very much.*" Likewise, the occupants of bungalow B04 noted that, "*the only thing that would stop me opening a window would be if a light was on while it was night time, to stop bugs getting in …*".

One barrier to action was cited by many of the interviewees, which is probably more important than all the other factors; the 'scepticism' people felt about the 'issue of overheating'. As an occupant of bungalow B04 put it "*here, we have the sort of heat where people think they should really do something about it, but after a few days it's gone, and it goes to the back of their minds…".* Such perceptions are likely to be widespread in the UK.

Whilst the provision of adaptive opportunities, and advice on how to capitalise on these, would be valuable, overcoming the belief that overheating is not a pressing matter, is more important. It is a barrier to the provision of adaptive opportunity, the taking of effective action, and to effective preparation for the heat waves and warmer summers that are to come as the climate warms.

5. Discussion

The study conducted here was short term and involved a small number of households. Although the detailed results from this research may not be generalisable to the wider UK stock of new houses and bungalows, they do offer some useful insights which could guide future work; not least, because the study succeeded in capturing data about overheating during a particularly hot spell of English summer weather.

The rich case studies were developed for each dwelling using the range of data collected through the OAST, which included floor layouts, glazing schematics, occupant information and interview transcripts. The data facilitated the investigation of what people do to cool overheated homes in the summer, enabling three lines of enquiry, 'what can occupants do?', 'what do occupants do?', and 'what do occupants not do and why?'.

Previous modelling research (e.g. Vellei *et al.*, 2017) and epidemiological data has identified bungalows and living spaces directly below roofs as having an elevated risk of summertime overheating. The observation that the bungalows in this study had larger window areas relative to their floor area than the new build houses, and yet had the same relative operable area for ventilation, is interesting and might point to a further factor contributing to overheating in bungalows.

The incidence of elevated temperatures was assessed using both static and adaptive overheating criteria. The sustained hot weather experienced during the monitoring period meant that the upper threshold of thermal comfort provided by the adaptive approach was higher than the CIBSE static threshold of 28^{o}C, even for Cat I, vulnerable, individuals. The occupant interviews revealed that adaptation in response to elevated temperatures occurred even for sleeping periods, e.g. changing duvets for sheets, the use of fans or moving to another room. As previously observed (Lomas and Porritt, 2017), adaptive criteria seem more appropriate for assessing overheating than static criteria and should be developed for use during the night time sleeping period.

Refurbishment and remodelling have been mentioned elsewhere as potentially exacerbating overheating risk (Lomas and Porritt, 2017). This study provided three concrete examples, all associated with bungalows; the conversion of a roof space into a bedroom, and the addition of conservatories to two dwellings. In all three cases, these were associated with elevated indoor temperatures, either in the space itself, or because the conservatory was a barrier to ventilating the adjacent space. It is clear that modifications, either by the present or previous homeowners, to suite their lifestyle, had had the unintended consequence of exacerbating overheating risk. From a regulatory perspective, this may indicate the need to ensure that post-occupancy developments do not place the dwelling at increased risk of overheating.

Security fears, born of experience or the perception of risk, and the ingress of insects, were reaffirmed as barriers to opening windows and hence to night-time ventilation cooling. Fans were used by some households as an alternative but the turbulent breeze they create was uncomfortable at night. The limited experience that the study participants had had of elevated temperatures, given that heatwaves and hot spells occur only occasionally in the UK Midlands, meant that they had not given much thought to what they might do to tackle overheating. For example, the opening of specific windows to achieve cross-ventilation was rare even though this strategy may have been effective and provided sensory feedback, which could positively reinforce behaviour.

Almost all adaptive actions require some level of physical exertion, and many require cognitive effort. Those who may be most vulnerable to elevated temperatures may be amongst those least able to take action, and also the most disadvantaged in planning actions that require premeditation. They may therefore need support, perhaps by providing passive or active cooling devices, or perhaps by using technology to capitalise on the adaptive opportunities that already exist in their home.

The overarching scepticism about the risks of overheating in the UK is, though, a serious barrier, and one that is likely to be widespread in the UK, but difficult for those concerned with public health to overcome.

6. Conclusions

Summer time overheating in UK homes is increasingly seen as a risk to health and well-being. New build houses and bungalows, a dwelling type preferred by the elderly, who are vulnerable to elevated temperatures, may be particularly at risk.

A small cohort of four houses and four bungalows, located in Loughborough in the English Midlands, were studied during an eight-day hot spell, during the summer of 2017. Four of the dwellings were occupied by people over 60, bungalow B03 by man over 80. Room temperatures were measured and the newly developed Overheating Adaptive Opportunities, Actions and Barriers Survey Tool, OAST, (Wright *et al.*, 2018), was deployed to understand the scope for, and inclination of, households to mitigate high summertime temperatures.

Temperatures were measured in the main bedroom and the functional living room, i.e. the room used daily by the occupants, rather than the builders' designated living room. The main bedrooms in all homes monitored over the hot spell were warm, exceeding 26^oC

for between 19 and 65 hours during the monitoring period. The bedroom in one bungalow (B03) was so hot that it would fail the CIBSE criterion of 26^{o}C/1% of annual hours, even if no high temperatures were recorded in the whole of the rest of the year. The functional living room in this bungalow was also hot, exceeding the CIBSE 28^{o}C/1% of annual hours criterion. This space was also severely overheated as measured by the CIBSE adaptive overheating criterion. Whilst the bedroom temperatures in all the dwellings might hinder quality sleep, the sustained high temperatures in bungalow B03, which was occupied by the 83 year-old are of most concern.

The OAST proved to be a useful tool for identifying the opportunities and barriers to avoiding summertime overheating. Further work to operationalise the tool could be useful for social care and health professionals and other seeking to protect vulnerable people from the risks of summertime overheating.

The survey revealed that the bungalows had substantially higher glazing-to-floor area ratios than the houses, yet very similar relative areas of operable windows. This could increase their risk of overheating by admitting more solar gain without providing any additional means of summertime ventilation. Post-construction remodelling of three bungalows further increased the risk of overheating. In one bungalow, a roof-space converted to create the main bedroom had inadequate ventilation, and in two others conservatory extensions prevented ventilation of the trapped spaces behind.

Interviews with the occupants identified barriers to the use of windows for summertime night-ventilation cooling. The security risk was the main concern, but the possibility of insects entering the house was also mentioned. However, the overarching barrier was the general lack of concern about summertime overheating. It was seen as an infrequent, short duration and unimportant phenomenon. This perception is, perhaps, the biggest barrier to effective preparation for heat waves, the provision of adaptive opportunity and the taking of effective action to curb summertime overheating.

7. Acknowledgements

This work was conducted as part of a research project pursued within the London-Loughborough Centre for Doctoral Research in Energy Demand. The Engineering and Physical Sciences Research Council (EPSRC) funding for the Centre is gratefully acknowledged (Grant EP/H009612/1).

8. References

AECOM (2010) ‘A1-SENSLR: MNB – Environmental Impact Assessment – Part 2: Environmental Statement’, in. Available at: https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/TR010010/TR010010-000318-MNB Part 6.1.11 Chapter 10 Noise.pdf.

Age UK (2017) *Later Life in the United Kingdom*. Available at: https://www.ageuk.org.uk/Documents/EN-GB/Factsheets/Later_Life_UK_factsheet.pdf?dtrk= true.

Baborska-Narożny, M., Stevenson, F. and Grudzińska, M. (2017) ‘Overheating in retrofitted flats: occupant practices, learning and interventions’, *Building Research & Information*. Taylor & Francis, 45(1–2), pp. 40–59. doi: 10.1080/09613218.2016.1226671.

Beizaee, A., Lomas, K. J. and Firth, S. K. (2013) ‘National survey of summertime temperatures and overheating risk in English homes’, *Building and Environment*, 65, pp. 1–17. doi: 10.1016/j.buildenv.2013.03.011.

BSI (2007) ‘EN 15251:2007: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics’, *British Standards Institute* p. 54. doi: 10.1520/E2019-03R13.Copyright.

CIBSE (2006) ‘CIBSE Guide A: Environmental design’. Chartered Institution of Building Services Engineers, London., p. 403. Available at: https://www.cambeep.eng.cam.ac.uk/References/cibse.

CIBSE (2013) The limits of thermal comfort: Avoiding overheating in European buildings. Technical memorandum, TM52, C*hartered Institution of Building Services Engineers,* London. Available at: http://www.cibse.org/Knowledge/knowledge- items/detail?id=a0q20000008I7f5AAC.

CIBSE (2017) Design methodology for the assessment of overheating risk in homes. Technical memorandum, TM59, *Chartered Institution of Building Services Engineers,* London doi: CIBSE TM59: 2017.

Cook, J. *et al.* (2016) 'Consensus on consensus: a synthesis of consensus estimates on human-caused global warming', *Environmental Research Letters*. IOP Publishing, 11(4), p. 48002. doi: 10.1088/1748-9326/11/4/048002.

Dengel, A. *et al.* (2016) *Overheating in dwellings*. Available at: https://www.bre.co.uk/filelibrary/Briefing papers/116885-Overheating-Guidance- v3.pdf.

Dengel, A. and Swainson, M. (2012) *Overheating in new homes: A review of the evidence*, *Research Review, Zero Carbon Hub*. Milton Keynes. Available at: http://www.zerocarbonhub.org/sites/default/files/resources/reports/Overheating_in_New_Homes-A_review_of_the_evidence_NF46.pdf.

DCLG (2012) *Investigation into Overheating in Homes: Literature Review*. *Department for Communities and Local Government.* Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/760 4/2185850.pdf.

DCLG (2015) English Housing Survey. *Department for Communities and Local Government*
doi: 10.1017/CBO9781107415324.004.

DEFRA (2015) Nuisance smells. *Department for Environment Food and Rural Affairs* Available at: https://www.gov.uk/guidance/nuisance-smells-how-councils-deal-with-complaints (Accessed: 14 July 2017).

DEFRA (2017) *U*K Climate Change Risk Assessment 2017. *Department for Environment Food and Rural Affairs.* Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/584281/uk-climate-change-risk-assess-2017.pdf.

GOS (2016) 'Future of an Ageing Population', *Government Office for Science* pp. 1–124. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/535187/gs-16-10-future-of-anageing-population.pdf.

Gray, D. E. (2004) *Doing research in the real world*. Sage Publications Ltd.

Gupta, R., Barnfield, L. and Gregg, M. (2017) 'Overheating in care settings: magnitude, causes, preparedness and remedies', *Building Research & Information*. Taylor & Francis, 45(1–2), pp. 83–101. doi: 10.1080/09613218.2016.1227923.

Hajat, S. *et al.* (2014) 'Climate change effects on human health: projections of temperature- related mortality for the UK during the 2020s, 2050s and 2080s.', *Journal of epidemiology and community health*, pp. 1–8. doi: 10.1136/jech-2013-202449.

Hulme, J., Beaumont, A. and Summers, C. (2013) 'Energy Follow-Up Survey 2011, Report 11 : Methodology', (288851). Available at: https://www.gov.uk/government/statistics/energy-follow-up-survey-efus-2011.

Kenney, W. L. and Munce, T. A. (2003) 'Invited Review: Aging and human temperature regulation', *Journal of Applied Physiology*, 95(6), pp. 2598–2603. doi: 10.1152/japplphysiol.00202.2003.

Kovats, R. S., Johnson, H. and Griffith, C. (2006) 'Mortality in southern England during the 2003 heat wave by place of death.', *Health statistics quarterly*, (29), pp. 6–8. Available at: http://www.ncbi.nlm.nih.gov/pubmed/16523675.

Lomas, K. J. and Kane, T. (2013) Summertime temperatures and thermal comfort in UK homes, *Building Research and Information*. Taylor & Francis, Vol. 41(3), pp. 259-280. doi: 10.1080/09613218.2013.757886.

Lomas, K. J. and Porritt, S. M. (2017) 'Overheating in buildings: lessons from research', *Building Research & Information*. Taylor & Francis, 45(1–2), pp. 1–18. doi: 10.1080/09613218.2017.1256136.

Mavrogianni, A. *et al.* (2014) 'The impact of occupancy patterns, occupant-controlled ventilation and shading on indoor overheating risk in domestic environments', *Building and Environment*. Elsevier Ltd, 78, pp. 183–198. doi: 10.1016/j.buildenv.2014.04.008.

Mavrogianni, A. *et al.* (2017) 'Inhabitant actions and summer overheating risk in London dwellings', *Building Research & Information*. Taylor & Francis, 45(1–2), pp. 119–142. doi: 10.1080/09613218.2016.1208431.

McGill, G. *et al.* (2016) 'Meta-analysis of indoor temperatures in new-build housing', *Building Research & Information*. Taylor & Francis, 0(0), pp. 1–21. doi: 10.1080/09613218.2016.1226610.

McLeod, R. S. and Swainson, M. (2017) 'Chronic overheating in low carbon urban developments in a temperate climate', *Renewable and Sustainable Energy Reviews*. Elsevier, 74(September 2016), pp. 201–220. doi: 10.1016/j.rser.2016.09.106.

Meinke, A. *et al.* (2017) 'Comfort-related feedforward information: occupants' choice of cooling strategy and perceived comfort', *Building Research & Information*. Taylor & Francis, 45(1–2), pp. 222–238.

doi: 10.1080/09613218.2017.1233774.
Met Office (2017) *Heat-health watch*. Available at: http://www.metoffice.gov.uk/public/weather/heat-health/#?tab=heatHealth (Accessed: 27 July 2017).
Morgan, C. *et al.* (2017) 'Overheating in Scotland: contributing factors in occupied homes', *Building Research & Information*. Taylor & Francis, 45(1–2), pp. 143–156. doi: 10.1080/09613218.2017.1241472.
Nicol, J. F. (2001) 'Characterising occupant behavior in buildings: Towards a stochastic model of occupant use of windows, lights, blinds heaters and fans', *Seventh International IBPSA Conference*, pp. 1073–1078.
Palmer, J. *et al.* (2016) 'Building Performance Evaluation Programme : Findings from domestic projects Making reality match design', (January). Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/497758/Domestic_Building_Performance_full_report_2016.pdf.
PHE (2015) Heatwave planfor England. P*ublic Health England*.Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/429572/Heatwave_plan_-Making_the_case_-_2015.pdf.
Symonds, P. *et al.* (2017) 'Overheating in English dwellings: comparing modelled and monitored large-scale datasets', *Building Research & Information*. Taylor & Francis, 45(1–2), pp. 195–208. doi: 10.1080/09613218.2016.1224675.
RAE (2010) Engineering a low carbon built environment: The discipline of building engineering physics. *The Royal Academy of Engineering*. Available at: https://www.raeng.org.uk/publications/reports/engineering-a-low-carbon-built- environment.
Vandentorren, S. *et al.* (2006) 'August 2003 Heat Wave in France: Risk Factors for Death of Elderly People Living at Home', *The European Journal of Public Health*, 16(6), pp. 583–
591. doi: 10.1093/eurpub/ckl063.
Vardoulakis, S. *et al.* (2015) 'Impact of climate change on the domestic indoor environment and associated health risks in the UK', *Environment International*. Elsevier B.V., 85, pp. 299–313. doi: 10.1016/j.envint.2015.09.010.
Vellei, M. *et al.* (2017) 'Overheating in vulnerable and non-vulnerable households', *Building Research & Information*. Taylor & Francis, 45(1–2), pp. 102–118. doi: 10.1080/09613218.2016.1222190.
WHO (1991) 'Indoor Environment: Health Aspects of Air Quality, thermal environment, light and noise', W*orld Health Organization*. pp. 17–21. Available at: http://whqlibdoc.who.int/hq/1990/WHO_EHE_RUD_90.2.pdf.
Wright D. L., Haines V. J. and Lomas K. J. (2018) the Overheating Adaptive Opportunities, Actions and Barriers Survey Tool (OAST). doi: 10.17028/rd.lboro.5943337. Available at: https://figshare.com/s/737bd510a8816e54b319

WORKSHOP 3

Personal Comfort Models

Invited Chairs:
Stefano Schiavon and Christoph van Treeck

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Personal comfort models – new paradigm in thermal comfort for occupant-centric environmental control

Joyce Kim[1], Stefano Schiavon[1], and Gail Brager[1]

[1] Center for the Built Environment, University of California, Berkeley, CA, USA

Abstract: A personal comfort model is a new approach to thermal comfort modeling that predicts an individual's thermal comfort response, instead of the average response of a large population. It leverages the Internet of Things and machine learning to learn individuals' comfort requirements directly from the data collected in their everyday environment. Its results could be aggregated to predict comfort of a population. To provide guidance on future efforts in this emerging research area, this paper presents a unified framework for personal comfort models. We first define the problem by providing a brief discussion of existing thermal comfort models and their limitations for real-world applications, and then review the current state of research on personal comfort models including a summary of key advances and gaps. We then describe a modeling framework to establish fundamental concepts and methodologies for developing and evaluating personal comfort models, followed by a discussion of how such models can be integrated into indoor environmental controls. Lastly, we discuss the challenges and opportunities for applications of personal comfort models for building design, control, standards, and future research.

Keywords: personal thermal comfort, machine learning, Internet of Things, occupant-centric environmental control, smart buildings

1. Introduction

Thermal comfort is an important goal for the built environment as it affects occupant satisfaction, health, and productivity. To understand what makes an environment thermally comfortable to the occupants, researchers have focused on developing empirical models that can represent human perception of thermal comfort in terms of the given conditions or factors. There are two main models that underpin the current practice of comfort management in buildings: predicted mean vote (PMV) and adaptive models. However, both PMV and adaptive models have inherent limitations when used to predict occupants' comfort in real buildings. First, both PMV and adaptive models show poor predictive accuracy when applied to a small group of people or individuals because they are designed to predict the average comfort of a large population (Auffenberg et al., 2015; van Hoof, 2008). Second, a full implementation of the PMV model requires very specific input variables (e.g., air speed, metabolic rate, clothing insulation) that are costly and difficult to obtain in the real-world settings and therefore, they are often assumed or simplified. Third, the models do not allow additions to their respective set of input variables; hence new variables that show relevance to the occupants' thermal comfort in the real-world settings cannot be incorporated in their predictions (e.g., sex, body mass index, time of day, etc.). Lastly, the model properties (e.g., function, coefficients) are fixed by the original data set (i.e., laboratory data for the PMV model, and field data for the adaptive models), and cannot be updated to reflect the actual comfort conditions of individuals in a particular setting.

To overcome the drawbacks listed above, we propose a new modeling approach called a ***personal comfort model***. A personal comfort model predicts individuals' thermal comfort responses instead of the average response of a large population. The key characteristics of personal comfort models are that they: (1) take an individual person as the unit of analysis rather than populations or groups of people; (2) use direct feedback from individuals (e.g., thermal sensation, preference, acceptability, pleasure) and additional relevant data (e.g., personal, environmental, technological), to train a model; (3) prioritize cost-effective and easily-obtainable data; (4) employ a data-driven approach, which allows flexible testing of different modeling methods and potential explanatory variables; and (5) have the capacity to adapt as new data is introduced to the model.

2. Review of current state of research

The opportunities associated with personal comfort models have generated significant interest within the research and industry communities. To better understand the current state of research and development on personal comfort models, we reviewed relevant literature published in the past ten years (Auffenberg et al., 2015; Cheung et al., 2017; Daum et al., 2011; Feldmeier and Paradiso, 2010; Gao and Keshav, 2013; Ghahramani et al., 2015; Jazizadeh et al., 2014; Jiang and Yao, 2016; Lee et al., 2017; Li et al., 2017; Liu et al., 2007; Rana et al., 2013; Zhao et al., 2014b, 2014a). Key advances made in this collective research about personal comfort models include (1) improved predictive power with 20-40% accuracy gains compared to conventional comfort models by employing machine learning algorithms, and (2) diversities in types of data and occupant feedback obtained from various sensors and connected devices, well beyond the traditional thermal comfort variables.

Current research gaps include:

- Lack of a unified modeling framework. Research primarily focuses on predictive accuracy of the model rather than developing a systematic approach to build and evaluate the model for general benefits.
- Lack of connection to thermal comfort fundamentals. Previous researchers, mainly outside the thermal comfort field, often apply their own interpretations or assumptions in their proposed models that are not necessarily grounded in existing thermal comfort research.
- Lack of vision for real-world integration. Past research is typically missing efforts to describe how the proposed models can be integrated into real-world systems to enable intelligent comfort management.
- Lack of industry standards. There have been no standardization efforts to guide the development and evaluation of personal comfort models and ensure their performance in building design and control.

3. A framework for personal comfort models

Developing a personal comfort model involves the following processes (see Figure 1), including:

- **Data collection** – determine what data will be the basis for the learning algorithms and how to collect it
- **Data preparation** – process and prepare raw data into the format ready for modeling
- **Model selection** – select learning algorithms appropriate for the given data and application goals
- **Model evaluation** – validate predictive performance of the model and readiness for its use in applications

- **Continuous learning** – update the model based on new data to ensure accuracy and relevance over time

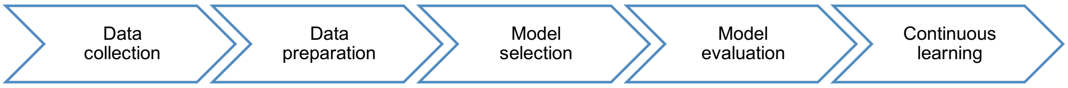


Figure 1. Modelling process of personal comfort models

3.1. Data collection

To model an individual's thermal comfort, we need data that: 1) expresses his/her perception of thermal comfort, and 2) describes the given conditions or factors (e.g., personal, environmental, etc.) influencing that perception. Table 1 lists the type of data and possible collection methods that can be used for the development of personal comfort models.

Table 1. Examples of data types and collection methods* for personal comfort models

Category	Data types
Thermal comfort perception[1]	Sensation, preference, acceptability, pleasure
Personal factors	
Physiological	Skin temperature[2], heart rate[2], metabolic rate Clothing insulation Sex, age, body mass index, health status (e.g., dementia)
Behavioral	Turning on/off fans or heater, thermostat adjustments, opening/closing windows
Environmental factors	
Indoor[3]	Air temperature, mean radiant temperature, operative temperature, relative humidity, air velocity
Outdoor[4]	Air temperature, running mean temperature, humidity, precipitation Climate, season
Other factors	Time, location, context (e.g., home, office, car, outdoor), occupancy type (e.g., private, shared) Thermal history, cultural expectations (e.g., dress code) Mechanical system settings[5] (e.g., thermostat setpoints), availability of occupant controls

*Frequently used data collection methods include [1]survey, [2]wearable sensors, [3]environmental sensors, [4]weather stations, [5]building automation systems, etc.

Data collection is more straightforward for some of these variables than others, and here are some of the key considerations for some of them. The Appendix includes additional criteria to consider.

- **Thermal comfort metrics:** Thermal comfort can be assessed using survey questionnaires that ask about thermal sensation, acceptability, preference, satisfaction, or a combination. The perceptions are then mapped to the measured physical conditions at the time. Thermal sensation is by far the most frequently used metric in personal comfort models due to its association with the PMV model, and an assumption is then made associating comfort with neutral sensation. Thermal acceptability can also be used with the assumption that "acceptability" is equated with "comfort". It is possible that even when people are not in their ideal state of comfort, they may still find it "acceptable", meaning that it is tolerable or not bad enough to complain. We think that, thermal preference is a closer measure of what ideal conditions would be, and can be effective if the objective is to use it for the control of HVAC (Heating, Ventilation, and Air Conditioning) systems because it suggests a direction of change. Thermal satisfaction is often used in the long-term assessment of buildings during post occupancy evaluations. It is important to understand that different metrics can lead to different assessment of comfort requirements, which can have different energy consequences (Berglund, 1979; Brager et al., 1993). Hence, one can consider the impact of different metrics on both comfort and energy outcome when selecting specific metrics to model individuals' thermal comfort.

- **Variations in scale construction:** The standards suggest the use of a 7-point ordered or continuous scale for thermal sensation ('hot' to 'cold'), a 3-point categorical scale for thermal preference ('warmer'/'no change'/'colder'), and a continuous or 7-point categorical scale for thermal acceptability ('acceptable' to 'unacceptable'). Although it would be ideal if researchers used standardized scales for consistency and easy comparisons between different models, that is not always the case. Some modelers (Ghahramani et al., 2015; Zhao et al., 2014b) have opted to modify or create new scales to satisfy their own modeling purposes (e.g., 11-point thermal preference scale, 5-point thermal sensation scale). The effects of varying scale points are not yet well understood in thermal comfort research and the existing ones have been challenged (Schweiker et al., 2017). A classic psychology experiment (Miller, 1956) recommends limiting the response options to 5-7 because our ability to make judgments significantly decreases when we are presented with more than 7 alternatives simultaneously.
- **Physiological and behavioral data:** Personal data about either comfort-related physiological states of the body or behavioral coping strategies are most commonly obtained via surveys. As such, the data collection is often stochastic and the data accuracy is difficult to validate due to the self-reported and self-measured nature of survey responses. Hence, one might supplement surveys with objective methods of collecting individual-specific data to ensure consistency and quality of the data that can be integrated into personal comfort models. As examples, research shows that wearable sensors or connected devices can provide continuous data tracking of occupants' physiological conditions (e.g., skin temperature, heart rate) (Choi et al., 2012; Hamatani et al., 2015; Ghahramani et al., 2016a; Cheng et al., 2017; Li et al., 2017) or behavioral actions (e.g., personal fan use, thermostat adjustments) (Bermejo et al., 2012; Li et al., 2017).
- **Challenging environmental measurement:** Radiant temperature and air velocity are often omitted or simplified in the development of personal comfort models, largely because modelers intentionally target easily obtainable data and the instrumentation to collect these variables is costly. However, several studies (Alfano et al., 2011) have shown that these variables significantly affect thermal comfort predictions. Efforts are underway to reduce the cost and increase the capabilities (e.g., wireless data transfer, longer battery life, reduced equipment size) of these instruments for scalable and automated data collection in practice (e.g., Hamilton wireless sensor (Andersen, 2017)).
- **Other influencing factors:** Other factors that may influence individuals' thermal comfort include, but are not limited to, time factors (e.g., hour, day, season) (Auffenberg et al., 2015; Chun et al., 2008); thermal conditioning systems and settings

(e.g., active or passive systems, heating/cooling setpoints, availability of occupant control) (Brager et al., 2004; de Dear and Brager, 1998); building types (e.g., home vs. office) (Karjalainen, 2009; Oseland, 1995); culture (e.g., socio-economic status, dress code) (Brager and de Dear, 1998; Shove, 2004); health, mood, demographic attributes (e.g., sex, age) (Indraganti and Rao, 2010; Karjalainen, 2007; van Hoof et al., 2017); and thermal history (e.g., living/working in air-conditioned vs. naturally ventilated buildings, temperature cycles and ramps, short and long term thermal exposure) (Brager and de Dear, 1998; Chun et al., 2008; Kolarik et al., 2009). Many of these factors can be easily obtained without instrumentation to record. Hence, efforts are needed to evaluate their importance in predicting individuals' thermal comfort.

3.2. Data preparation

Personal comfort models integrate highly heterogeneous data sets that are often presented in different structures, granularity, and volume. Therefore, it is important to prepare the raw data into a format ready for modelling. This involves (1) *cleaning* missing values, outliers, and measurement errors that can misrepresent the general trends in observed data; (2) *feature scaling* to normalize numerical data into a consistent range and mean when different scales can skew the model outcome (e.g., distance-based clustering) or affect computational speed (e.g., gradient descent); (3) *aggregating* to reduce the volume and granularity of the data by summarizing raw values into statistically representative values (e.g., mean) or grouping into discrete categories (e.g., Yes/No); (4) *feature creation* to explore new variables (e.g., rate of temperature change) drawn from the raw data that may influence individuals' thermal comfort; (5) *merging* to combine time-series data from heterogeneous sources with different logging intervals and frequencies; and (6) *partitioning* to split the data set into training and test sets in order to evaluate and fine-tune the trained model based on new data.

3.3. Model selection

Personal comfort models often explore non-traditional data types and relationships in order to better predict individuals' thermal comfort. Because of this, there is a strong interest in adopting machine learning to make predictions directly from the patterns learned from the data. This is a significant departure from the traditional modelling approach which was predominantly based on statistical modelling (e.g., linear regression) to discover generalizable findings. Below we describe popular machine learning algorithms that can be used for personal comfort models (Witten et al., 2016).

- **Regression algorithms** predict response variables by establishing mathematical relationships between different variables. Examples include ordinary least squares, linear, and logistic regressions.
- **Decision tree algorithms** construct a tree-like model that predicts the target response by learning decision rules inferred from the data. Examples include Classification and Regression Tree (CART) and conditional decision trees.
- **Bayesian algorithms** apply Bayes' Theorem to make predictions based on the probability of prior events. Examples include Naïve Bayes and Bayesian Network.
- **Kernel algorithms** map input data into a higher dimensional vector space to model non-linear relationships or patterns. Examples include Support Vector Machines, Radial Basis Function, Gaussian Process, and Linear Discriminant Analysis.

3.4. Model evaluation

The goal of model evaluation is to assess how good the model is in predicting individuals' thermal comfort, identify aspects of the model in need of improvement, and provide the basis for comparing different models. We list the following criteria that can help the evaluation process.

- **Prediction accuracy** assesses how correctly the model predicts. This is typically measured based on the differences between the predicted outcome and true outcome.
- **Prediction consistency** assesses how much the model predictions vary from one sample to another. This helps to evaluate the generalizability of a model outside of the training samples.
- **Model convergence** assesses whether the model has converged its learning to produce a stable prediction behavior. This helps to determine a quantifiable target for data collection and model performance.

3.5. Continuous learning

Both human perception and physical conditions of thermal comfort can change over time. For example, seasons (Nicol et al., 1999) and prevailing outside weather (Rijal et al., 2010) can influence people's preference for cooling and heating. Therefore, personal comfort models should adapt to changes observed in the new data, when available, in order to stay relevant and accurate over time. Previous studies suggest the following methods to continuously update personal comfort models: (1) remove statistically irrelevant points from the data set as new data is entered (Ghahramani et al., 2015); (2) apply forgetting factors to give more weight to recent data and less weight to historical data (Zhao et al., 2014b); (3) remove samples older than one month within similar temperature ranges when new data is entered (Daum et al., 2011); and (4) perform full relearning upon every new data entry (Auffenberg et al., 2015). While these proposed methods show how personal comfort models can adapt to changes over time, only Ghahramani et al. (Ghahramani et al., 2015) tested their proposed method against an actual dataset. Hence, more efforts are needed to evaluate these methods as well as other promising methods against real data. Lastly, techniques for continuous learning should be performed efficiently in a scalable fashion to handle the growing volume of data collected from various connected sensors and devices.

4. Integration into thermal controls

Integrating personal comfort models into indoor environmental control of buildings or other systems (e.g., vehicle) offers an opportunity to respond to individuals' comfort needs and desires in everyday comfort management. Such integration requires the following major technological components, as shown in Figure 2.

- **Connected sensors and devices** enable collection of input data for the development of personal comfort models (e.g., thermal comfort perception, personal and environmental measurements).
- **Network and connectivity** enables data transfer from various sensors and devices to a central server.
- **A central server** hosts the function of data warehousing, analytics, optimization, and actuation commands.
- **The controllers** receive actuation commands from the server to drive the operation of thermal conditioning systems.

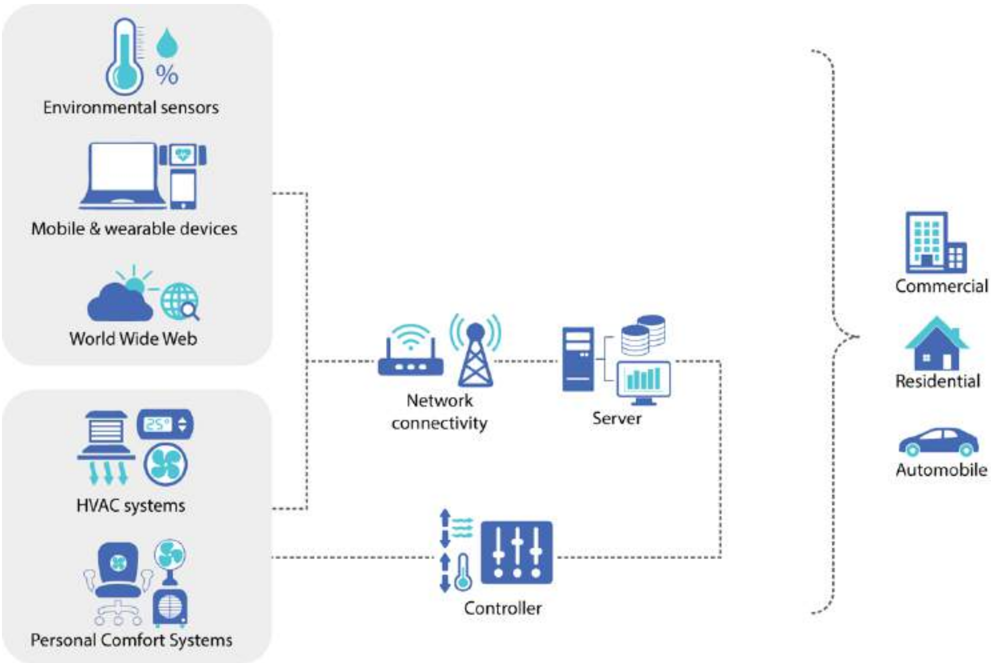


Figure 2. System architecture for occupant-responsive environmental control

5. Discussion

We discuss some of the challenges and opportunities for applications of personal comfort models by answering the following critical questions.

1) How can we ensure sufficient collection of occupant feedback on thermal comfort?

Collecting sufficient data that expresses individuals' perception of thermal comfort is critical. Currently, this data is captured through surveys. However, securing consistent feedback is difficult (Rana et al., 2013). Some strategies may help, such as using survey reminders via email or pop-up notifications. Another option is to pool relevant survey responses from other occupants in order to increase the data size when there are insufficient data points to develop a personal comfort model (Schumann et al., 2010). The relevance can be determined based the degree of similarity in environmental conditions (e.g., temperature ranges), building types (e.g., naturally-ventilated vs. mechanically-conditioned), or personal attributes (e.g., age, sex). Proxy variables that supplement or replace direct survey responses on thermal comfort after training are also a valid path. Research has shown correlations between individuals' thermal comfort survey responses and thermal control behavior (e.g., thermostat adjustments) (Bermejo et al., 2012; Kim et al., 2018) and physiological conditions (e.g., heart rate, skin temperature) (Choi et al., 2012; Ghahramani et al., 2016a; Choi and Yeom, 2017; Dai et al., 2017; Nkurikiyeyezu et al., 2017), both of which can be measured continuously via non-intrusive monitoring technologies (e.g., smart thermostats, wearable sensors). Hence, they could potentially be used in personal comfort models as proxy variables to infer individuals' thermal comfort.

2) How can personal comfort models be generalizable to a larger population?

Personal comfort models are designed to predict thermal comfort for a single person; hence, they are not necessarily directly applicable to other occupants. However, as the size and diversity of data increases, repeatable patterns may surface that can be generalized to a larger population. For example, grouping of models may form to provide general descriptions about thermal comfort that can be attributed to certain population segments (e.g., BMI, age) or space types (e.g., office, home, car). These repeatable patterns can serve as the foundation for creating generalizable thermal comfort profiles. The profiles can provide several benefits to the building industry at large, including serving as: 1) reasonable baseline models that can be readily applied to a new person who does not yet have a personal comfort model or whose personal comfort model is still under development; 2) a set of thermal comfort profiles that can be used for building/system design and operation to better characterize specific thermal comfort requirements across different segmentations of the building population; and 3) a more realistic building energy estimation that reflects the differences in individuals' thermal comfort requirements in HVAC control settings

3) *How can we resolve the differences in thermal preferences among the occupants in shared spaces?*

This is not a new problem. It exists whether personal comfort models are available or not. With personal comfort models, such differences are revealed and quantified so that they can be addressed. The existing studies have explored two approaches regarding this issue: 1) consensus-based solutions, and 2) technological solutions (for either individuals or groups), often with overlaps between them.

For consensus-based solutions, Jazizadeh et al. (2014) selected a temperature setpoint that minimized the error between everyone's preferred and actual room temperatures. In the case that acceptable comfort levels could not be achieved for all occupants in a zone, Ghahramani et al. (2014) incrementally increased the acceptable temperature range of individuals within a pre-defined discomfort threshold. Murakami et al. (2007) determined the temperature setpoint by a majority vote. Lee et al. (2008) assigned varying priorities to different occupant groups (e.g., more emphasis on employees over visitors) in order to determine optimal temperature in public zones. Although these strategies needed a system to ultimately adjust the setpoint, the underlying decision making was consensus-based.

For technological solutions, Erickson and Cerpa (2012) enabled real-time thermostat setpoint adjustments based on occupants' requests to address the comfort issues in shared spaces as they occur. However, this scheme can introduce potential gaming of the system and biases toward more vocal occupants. To reduce these effects, they limited the vote per person to one in every 10 min and averaged the votes to determine the new temperature setpoint at the end of the voting period. Another example of a technological solution used personal comfort systems (PCS) to provide local heating and cooling without affecting others in the same space (Zhang et al., 2015). With PCS, individuals can address their own comfort needs or desires in shared spaces, and therefore be less vulnerable to the thermal conditions set by the centralized systems. In shared spaces, increasing the granularity of the control (e.g., lowered number of occupants per variable air volume box) is also a technological solution that could help.

4) *What is the impact on energy when using personal comfort models to make control decisions?*

The ultimate goal for improved building operation is to simultaneously improve both energy and comfort performance, but many people still view this as a tradeoff where you can only improve one at the expense of the other. Conceptually, personal comfort models can help improve performance in both comfort and energy by providing information about individuals' thermal comfort requirements, such as acceptable temperature limits for a given space. If the acceptable temperature limits are greater than the default temperature setpoint ranges, one can expect HVAC energy savings (i.e., fans, reheat) by widening the temperature setpoints

(Ghahramani et al., 2016b; Hoyt et al., 2015; Schiavon and Melikov, 2008; Sekhar, 1995). Examples of demonstrated energy savings include: 10% energy savings by implementing real-time setpoint control using individuals' online requests (2012); more than 20% savings using the consensus-based temperature control strategy (2007); up to 24% by adjusting temperature setpoints based on hot or cold complaints by the occupants (2010); 39% reduction in daily average airflow by resetting temperature setpoints according to occupants' preferred temperatures (2014); and 51% reduction in daily average air flow by allowing occupants' comfort level to slightly deviate from their preferred temperatures (2014). These savings are based on the volume of energy consumption (i.e., kWh). The buildings can also save on the utility cost (i.e., $) under variable rates and demand charges by dynamically adjusting HVAC loads during peak hours.

5) What is the role of standards with respect to personalized thermal comfort models?

Existing standards take prescriptive approaches to thermal comfort provision by specifying detailed criteria of an acceptable thermal environment that would satisfy the majority of occupants (i.e., 80%). However, a very small percentage of buildings fulfil this objective. Data-driven occupant-centric comfort management is gaining attention among progressive and forward-thinking building professionals (Talon and Goldstein, 2015). Personal comfort models can play an essential role in this new paradigm by generating accurate predictions of individuals' comfort requirements and closing the loop between occupants and HVAC systems. However, the existing personal comfort models have been independently developed by both academics and corporations and are not always in agreement with the standards' approach to thermal comfort assessment. Hence, these research efforts need to be guided in order to assure accurate and reliable performance of the model, and to create a more standard protocol for different applications.

Standards can play an important role by allowing a performance-based approach to thermal comfort provision, thus allowing more flexibility in buildings to accommodate context- and occupant-specific comfort requirements that cannot currently be satisfied by the traditional prescriptive approach. Towards this end, standards should provide guidelines for this performance-based approach, addressing data collection, privacy and security requirements for data storage and access, and the development, testing, validation, and implementation of the custom models in buildings.

6. Conclusions

A personal comfort model is a new approach to thermal comfort modeling that predicts individual's thermal comfort responses, instead of the average response of a large population. In particular, it leverages Internet of Things and machine learning to learn individuals' comfort requirements directly from the real-world data; hence, it can provide individual-specific and context-relevant data to improve the level of thermal comfort among occupants and optimize energy use in buildings. With advances in comfort technologies penetrating the built environment, the demand for personalized thermal experience will increase. To meet this demand, we should do research to turn the insights generated from personal comfort models into actionable control strategies in order to yield a tangible impact on people's comfort satisfaction in buildings. We hope that our paper has provided a foundation for that to occur.

7. Acknowledgements

Joyce Kim was supported by the Center for the Built Environment at University of California, Berkeley, and by the California Energy Commission Public Interest Energy Research (PIER)

Buildings Program under Contract PIR-12-026. Stefano Schiavon was supported by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program.

8. References

Alfano, F.R. d'Ambrosio, Palella, B.I., Riccio, G., 2011. The role of measurement accuracy on the thermal environment assessment by means of PMV index. Building and Environment 46, 1361–1369. https://doi.org/10.1016/j.buildenv.2011.01.001

Andersen, M., 2017. Hamilton open-source hardware.

Auffenberg, F., Stein, S., Rogers, A., 2015. A personalised thermal comfort model using a Bayesian Network, in: Proceedings of the Twenty-Fourth International Joint Conference on Artificial Intelligence (IJCAI 2015). pp. 2547–2553.

Berglund, L.G., 1979. Thermal acceptability. ASHRAE Transactions 85, 825–834.

Bermejo, P., Redondo, L., de la Ossa, L., Rodríguez, D., Flores, J., Urea, C., Gámez, J.A., Puerta, J.M., 2012. Design and simulation of a thermal comfort adaptive system based on fuzzy logic and on-line learning. Energy and Buildings 49, 367–379. https://doi.org/10.1016/j.enbuild.2012.02.032

Brager, G., Fountain, M., Benton, C., Arens, E.A., Bauman, F., 1993. A Comparison of Methods for Assessing Thermal Sensation and Acceptability in the Field, in: Oseland, N. (Ed.), Proceedings of Thermal Comfort: Past, Present and Future. British Research Establishment, Watford, United Kingdom.

Brager, G., Paliaga, G., De Dear, R., 2004. Operable windows, personal control and occupant comfort. ASHRAE Transactions 110, 17–35.

Brager, G.S., de Dear, R.J., 1998. Thermal adaptation in the built environment: a literature review. Energy and Buildings 27, 83–96. https://doi.org/10.1016/S0378-7788(97)00053-4

Cheng, X., Yang, B., Olofsson, T., Liu, G., Li, H., 2017. A pilot study of online non-invasive measuring technology based on video magnification to determine skin temperature. Building and Environment 121, 1–10. https://doi.org/10.1016/j.buildenv.2017.05.021

Cheung, T.C., Schiavon, S., Gall, E.T., Jin, M., Nazaroff, W.W., 2017. Longitudinal assessment of thermal and perceived air quality acceptability in relation to temperature, humidity, and CO2 exposure in Singapore. Building and Environment 115, 80–90. https://doi.org/10.1016/j.buildenv.2017.01.014

Choi, J.-H., Loftness, V., Lee, D.-W., 2012. Investigation of the possibility of the use of heart rate as a human factor for thermal sensation models. Building and Environment 50, 165–175. https://doi.org/10.1016/j.buildenv.2011.10.009

Choi, J.-H., Yeom, D., 2017. Study of data-driven thermal sensation prediction model as a function of local body skin temperatures in a built environment. Building and Environment 121, 130–147. https://doi.org/10.1016/j.buildenv.2017.05.004

Chun, C., Kwok, A., Mitamura, T., Miwa, N., Tamura, A., 2008. Thermal diary: Connecting temperature history to indoor comfort. Building and Environment 43, 877–885. https://doi.org/10.1016/j.buildenv.2007.01.031

Dai, C., Zhang, H., Arens, E., Lian, Z., 2017. Machine learning approaches to predict thermal demands using skin temperatures: Steady-state conditions. Building and Environment 114, 1–10. https://doi.org/10.1016/j.buildenv.2016.12.005

Daum, D., Haldi, F., Morel, N., 2011. A personalized measure of thermal comfort for building controls. Building and Environment 46, 3–11. https://doi.org/10.1016/j.buildenv.2010.06.011

de Dear, R.J., Brager, G.S., 1998. Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions 104, 145–167.

Erickson, V.L., Cerpa, A.E., 2012. Thermovote: participatory sensing for efficient building HVAC conditioning, in: Proceedings of 4th ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings (BuildSys). pp. 9–16. https://doi.org/10.1145/2422531.2422534

Feldmeier, M., Paradiso, J.A., 2010. Personalized HVAC control system, in: Internet of Things (IOT), 2010. Presented at the Internet of Things (IOT), 2010, pp. 1–8. https://doi.org/10.1109/IOT.2010.5678444

Gao, P.X., Keshav, S., 2013. SPOT: a smart personalized office thermal control system, in: Proceedings of the Fourth International Conference on Future Energy Systems. ACM, pp. 237–246. https://doi.org/10.1145/2487166.2487193

Ghahramani, A., Castro, G., Becerik-Gerber, B., Yu, X., 2016a. Infrared thermography of human face for monitoring thermoregulation performance and estimating personal thermal comfort. Building and Environment 109, 1–11. https://doi.org/10.1016/j.buildenv.2016.09.005

Ghahramani, A., Jazizadeh, F., Becerik-Gerber, B., 2014. A knowledge based approach for selecting energy-aware and comfort-driven HVAC temperature set points. Energy and Buildings 85, 536–548. https://doi.org/10.1016/j.enbuild.2014.09.055

Ghahramani, A., Tang, C., Becerik-Gerber, B., 2015. An online learning approach for quantifying personalized thermal comfort via adaptive stochastic modeling. Building and Environment 92, 86–96. https://doi.org/10.1016/j.buildenv.2015.04.017

Ghahramani, A., Zhang, K., Dutta, K., Yang, Z., Becerik-Gerber, B., 2016b. Energy savings from temperature setpoints and deadband: Quantifying the influence of building and system properties on savings. Applied Energy 165, 930–942. https://doi.org/10.1016/j.apenergy.2015.12.115

Hamatani, T., Uchiyama, A., Higashino, T., 2015. Real-Time Calibration of a Human Thermal Model with Solar Radiation Using Wearable Sensors, in: Proceedings of the 2015 Workshop on Wearable Systems and Applications. ACM, pp. 45–50.

Hoyt, T., Arens, E., Zhang, H., 2015. Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. Building and Environment 88, 89–96. https://doi.org/10.1016/j.buildenv.2014.09.010

Indraganti, M., Rao, K.D., 2010. Effect of age, gender, economic group and tenure on thermal comfort: A field study in residential buildings in hot and dry climate with seasonal variations. Energy and Buildings 42, 273–281. https://doi.org/10.1016/j.enbuild.2009.09.003

Jazizadeh, F., Ghahramani, A., Becerik-Gerber, B., Kichkaylo, T., Orosz, M., 2014. Human-Building Interaction Framework for Personalized Thermal Comfort-Driven Systems in Office Buildings. Journal of Computing in Civil Engineering 28, 2–16. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000300

Jiang, L., Yao, R., 2016. Modelling personal thermal sensations using C-Support Vector Classification (C-SVC) algorithm. Building and Environment 99, 98–106. https://doi.org/10.1016/j.buildenv.2016.01.022

Karjalainen, S., 2009. Thermal comfort and use of thermostats in Finnish homes and offices. Building and Environment 44, 1237–1245. https://doi.org/10.1016/j.buildenv.2008.09.002

Karjalainen, S., 2007. Gender differences in thermal comfort and use of thermostats in everyday thermal environments. Building and environment 42, 1594–1603. https://doi.org/10.1016/j.buildenv.2006.01.009

Kim, J., Zhou, Y., Schiavon, S., Raftery, P., Brager, G., 2018. Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning. Building and Environment 129, 96–106. https://doi.org/10.1016/j.buildenv.2017.12.011

Kolarik, J., Toftum, J., Olesen, B.W., Shitzer, A., 2009. Occupant responses and office work performance in environments with moderately drifting operative temperatures (RP-1269). HVAC&R Research 15, 931–960.

Lee, H., Choi, J.S., Elmasri, R., 2008. A conflict resolution architecture for the comfort of occupants in intelligent office, in: Intelligent Environments, 2008 IET 4th International Conference On. IET, pp. 1–8. https://doi.org/10.1049/cp:20081135

Lee, S., Bilionis, I., Karava, P., Tzempelikos, A., 2017. A Bayesian approach for probabilistic classification and inference of occupant thermal preferences in office buildings. Building and Environment 118, 323–343. https://doi.org/10.1016/j.buildenv.2017.03.009

Li, D., Menassa, C.C., Kamat, V.R., 2017. Personalized human comfort in indoor building environments under diverse conditioning modes. Building and Environment 126, 304–317. https://doi.org/10.1016/j.buildenv.2017.10.004

Liu, W., Lian, Z., Zhao, B., 2007. A neural network evaluation model for individual thermal comfort. Energy and Buildings 39, 1115–1122. https://doi.org/10.1016/j.enbuild.2006.12.005

Miller, G.A., 1956. The magical number seven, plus or minus two: some limits on our capacity for processing information. Psychological review 63, 81.

Murakami, Y., Terano, M., Mizutani, K., Harada, M., Kuno, S., 2007. Field experiments on energy consumption and thermal comfort in the office environment controlled by occupants' requirements from PC terminal. Building and Environment 42, 4022–4027. https://doi.org/10.1016/j.buildenv.2006.05.012

Nicol, J.F., Raja, I.A., Allaudin, A., Jamy, G.N., 1999. Climatic variations in comfortable temperatures: the Pakistan projects. Energy and Buildings 30, 261–279. https://doi.org/10.1016/S0378-7788(99)00011-0

Nkurikiyeyezu, K.N., Suzuki, Y., Lopez, G.F., 2017. Heart rate variability as a predictive biomarker of thermal comfort. Journal of Ambient Intelligence and Humanized Computing 1–13. https://doi.org/10.1007/s12652-017-0567-4

Oseland, N.A., 1995. Predicted and reported thermal sensation in climate chambers, offices and homes. Energy and Buildings 23, 105–115. https://doi.org/10.1016/0378-7788(95)00934-5

Rana, R., Kusy, B., Jurdak, R., Wall, J., Hu, W., 2013. Feasibility analysis of using humidex as an indoor thermal comfort predictor. Energy and Buildings 64, 17–25. https://doi.org/10.1016/j.enbuild.2013.04.019

Rijal, H.B., Yoshida, H., Umemiya, N., 2010. Seasonal and regional differences in neutral temperatures in Nepalese traditional vernacular houses. Building and Environment 45, 2743–2753. https://doi.org/10.1016/j.buildenv.2010.06.002

Schiavon, S., Melikov, A.K., 2008. Energy saving and improved comfort by increased air movement. Energy and buildings 40, 1954–1960. https://doi.org/10.1016/j.enbuild.2008.05.001

Schumann, A., Wilson, N., Burillo, M., 2010. Learning User Preferences to Maximise Occupant Comfort in Office Buildings, in: García-Pedrajas, N., Herrera, F., Fyfe, C., Benítez, J.M., Ali, M. (Eds.), Trends in Applied Intelligent Systems, Lecture Notes in Computer Science. Springer Berlin Heidelberg, pp. 681–690. https://doi.org/10.1007/978-3-642-13022-9_68

Schweiker, M., Fuchs, X., Becker, S., Shukuya, M., Dovjak, M., Hawighorst, M., Kolarik, J., 2017. Challenging the assumptions for thermal sensation scales. Building Research & Information 45, 572–589. https://doi.org/10.1080/09613218.2016.1183185

Sekhar, S.C., 1995. Higher space temperatures and better thermal comfort - a tropical analysis. Energy and Buildings 23, 63–70. https://doi.org/10.1016/0378-7788(95)00932-N

Shove, E., 2004. Comfort, Cleanliness and Convenience: the Social Organization of Normality. Berg Publishers.

Talon, C., Goldstein, N., 2015. Smart offices: how intelligent building solutions are changing the occupant experience, Intel-sponsored white paper. Navigant Consulting, Inc.

van Hoof, J., 2008. Forty years of Fanger's model of thermal comfort: comfort for all? Indoor Air 18, 182–201. https://doi.org/10.1111/j.1600-0668.2007.00516.x

van Hoof, J., Schellen, L., Soebarto, V., Wong, J.K.W., Kazak, J.K., 2017. Ten questions concerning thermal comfort and ageing. Building and Environment 120, 123–133. https://doi.org/10.1016/j.buildenv.2017.05.008

Witten, I.H., Frank, E., Hall, M.A., Pal, C.J., 2016. Data mining: practical machine learning tools and techniques, 4th ed. Morgan Kaufmann.

Zhang, H., Arens, E., Zhai, Y., 2015. A review of the corrective power of personal comfort systems in non-neutral ambient environments. Building and Environment 91, 15–41. https://doi.org/10.1016/j.buildenv.2015.03.013

Zhao, Q., Zhao, Y., Wang, F., Jiang, Y., Jiang, Y., Zhang, F., 2014a. Preliminary study of learning individual thermal complaint behavior using one-class classifier for indoor environment control. Building and Environment 72, 201–211. https://doi.org/10.1016/j.buildenv.2013.11.009

Zhao, Q., Zhao, Y., Wang, F., Wang, J., Jiang, Y., Zhang, F., 2014b. A data-driven method to describe the personalized dynamic thermal comfort in ordinary office environment: From model to application. Building and Environment 72, 309–318. https://doi.org/10.1016/j.buildenv.2013.11.008

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Personal thermal comfort models based on physiological parameters measured by wearable sensors

Shichao Liu[1,3], Ming Jin[2], Hari Prasanna Das[2], Costas J. Spanos[2], Stefano Schiavon[1]

[1] Center for the Built Environment, University of California, Berkeley, CA, USA, sliu8@wpi.edu;
[2] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA, USA;
[3] Department of Civil and Environmental Engineering, Worcester Polytechnic Institute, MA, USA

Abstract: Existing HVAC systems involve little feedback from indoor occupants, resulting in unnecessary cooling/heating waste and high percentage of discomfort. In addition, large thermal preference variance amongst people requires the development of personal thermal comfort models, rather than group-based methodologies such as predicted mean vote (PMV). This study focuses on assessing wearable solutions with the aim to predict personal thermal preference. We collected physiological signals (e.g., skin temperature, heart rate) of 14 subjects (6 female and 8 male adults) and environmental parameters (e.g., air temperature, wind speed, solar radiation, precipitation) for two weeks (at least 20 hr/d) to infer personal real-time thermal preference. The subjects reported their real-time thermal sensation and preference using cell-phones approximately every hour. We trained a Random Forest algorithm using data collected from individuals to develop a personal comfort model with the objective to predict thermal preference. The results show that subjects expressed needs for "warmer" or "cooler" conditions at about 30% (from 21% to 88%) of their daily time on average, implying the strong demand for a personalized indoor thermal comfort. In addition, the personal comfort model using Random Forest can infer individual thermal preference with a mean accuracy of 75% (53 - 93%) using physiological and environmental parameters, demonstrating the strengths of the proposed data-driven method.

Keywords: Thermal preference, physiological signals/responses, Random Forest, skin temperature, heart rate

1. Introduction

Creating a thermally comfortable indoor environment for occupants can lead to improved job satisfaction, productivity and well-being. Only 40% of the occupant in US commercial buildings are satisfied with the thermal environment (Karmann et al., 2018). Perceived productivity was found reduced when thermal preference moved away from "no change" (McCartney and Humphreys, 2002). Incorporating occupants' thermal comfort in the control of building systems thermal environment saves heating, ventilation, and air conditioning (HVAC) energy consumption (Erickson and Cerpa, 2012; Hang-yat and Wang, 2013; Nguyen and Aiello, 2013; Nouvel and Alessi, 2012; Purdon et al., 2013; Sarkar et al., 2016).

One challenge to non-intrusively incorporate each occupant's feedback on the thermal environment is to accurately predict thermal comfort in the dynamic, non-uniform, and real environment. The most popular thermal comfort model, the predicted mean vote (PMV) and adaptive model, has been proved to have a low predicting power (Humphreys and Fergus Nicol, 2002; Kim et al., 2018a). The effects of individual difference in physiological, psychological, and behavioral factors are not considered in these models. Rather, a personal comfort model is a new approach to thermal comfort modeling that predicts an individual's thermal comfort response, instead of the average response of a large population (Kim et al., 2018b). Personal comfort models have a much higher predicting power than PMV and adaptive model owning to additional consideration of personal factors (Kim et al., 2018a). The models can be based on environmental parameters (e.g., air temperature, location, relative humidity) (Cheung et al., 2017), occupant feedback (e.g., online voting like Comfy) (Ghahramani et al., 2015; Kim et al., 2018a), occupant behaviour (e.g., thermostat setpoints like Nest), and physiological parameters (e.g., skin temperature, heart rate) (Chaudhuri et al., 2018; Choi and Loftness, 2012; Choi et al., 2012; Huang et al., 2015; Sim et al., 2016).

Occupants' physiological parameters could be measured by using infrared thermography (Ranjan and Scott, 2016) or wearable sensors (Ghahramani et al., 2016; Li et al., 2017a; Shen et al., 2012). The major challenges of infrared thermography and occupant behavior are either single parameter (e.g., skin temperature) tracking or difficulties in long-term monitoring in a free-living environment. Security is also a concern. By contrast, wearable sensors that are capable of measuring physiological signals and other parameters without relying on stationary infrastructure, are suitable for the prediction of personal thermal comfort in real life. Other benefits include cost, market penetration, privacy and opportunities to be infused in health monitoring. Moreover, wearable fitness trackers have become broadly available, such as Fitbit (Fitbit Inc., U.S.), Apple Watch (Apple Inc., U.S.) and Garmin (Garmin Ltd., U.S.). The emerging sensing technology provides the opportunities to apply the measured data to infer thermal comfort. For instance, wearable sensors were deployed together with in-home environmental sensors to predict thermal comfort in households (Huang et al., 2015). Occupants' real-time feedback on thermal preference was predicted by using physiological data (e.g., skin temperature, heart rate, activities) along with indoor environmental parameters (e.g., air temperature and humidity) and was incorporated into building system control, creating a human-in-the-loop system (Li et al., 2017).

Capturing the transitions among different thermal environments were found a challenge by wearable sensors. Most recent studies on applying wearable sensors to predict thermal comfort were conducted with participants restrained in a laboratory (Chaudhuri et al., 2018; Ghahramani et al., 2016; Sim et al., 2016; Sugimoto, 2013). Furthermore, occupants' diverse daily activities, such as cooking or commuting, have been rarely included in previous investigations. The feasibility and accuracy of personal thermal comfort prediction for real-life wearers are still unclear. The knowledge gap could be addressed probably only by continuously tracking occupants for a long-term.

In addition, it is worth attention that the accuracies of wearable sensors might cause uncertainties to thermal comfort inference. However, very few studies have reported the validation of sensors' measuring accuracies. In a laboratory environment, physiological signals measured and environmental data by commercially-off-the-shelf sensors were applied to train an algorithm to calculate PMV (Abdallah et al., 2016). The study pointed out that existing sensors need to be improved to increase accuracy, which was also affirmed by a recent study (Barrios and Kleiminger, 2017).

The objective of this study is to develop personal thermal comfort models using physiological and environmental data collected by wearable sensors. Compared to existing technologies, such non-intrusive solutions do not disturb occupants for survey input after personal comfort models have been trained. The models can be used for the control personal comfort systems but they can also be applied to general mechanical systems in buildings or vehicles.

2. Methodology

Different from group-average models such as the PMV and adaptive model, a personal model should be specifically developed for an occupant to account for the great variation in personal factors. Personal models might have various formats for different occupants. As such, personal models are likely inexplicitly determined using data-driven methods such as continuous training of machine learning algorithms over streaming data. Figure 1 displays the framework of personal thermal comfort modeling that can be used for building system control.

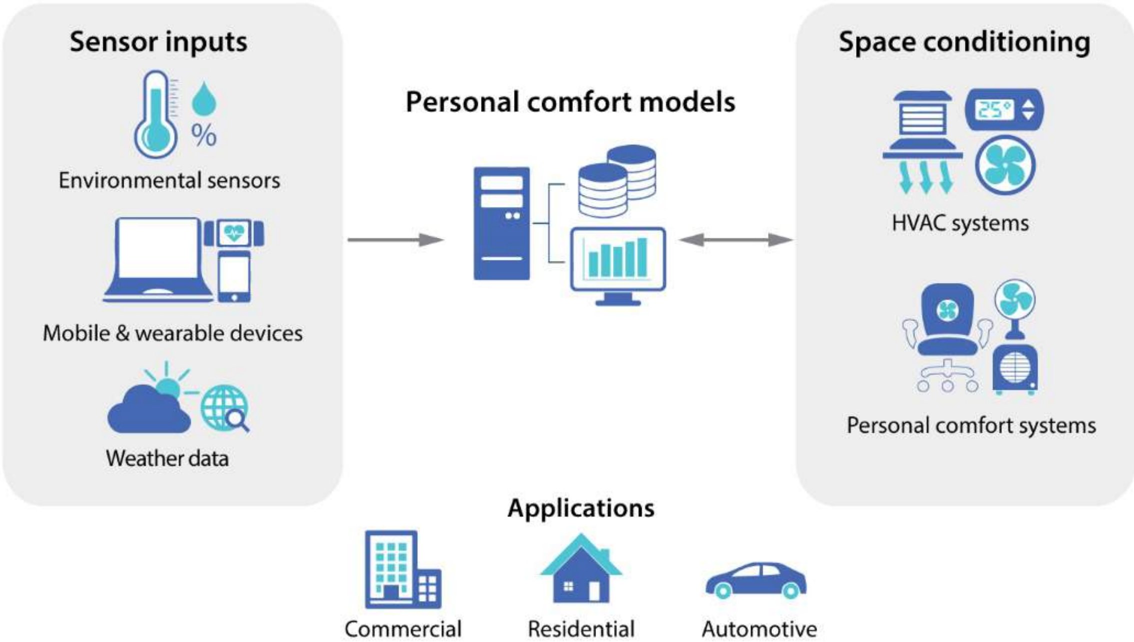


Figure 1. Framework of personal thermal comfort modelling. (Adapted from Kim et al., 2018b)

In this study, we collected and formatted physiological responses from human subjects and applied machine learning algorithms to train a personal thermal comfort model for each subject. Thermal sensation and preference data from surveys were utilized as ground truth for model development and evaluation.

2.1. Subjects

We initially recruited twenty subjects (half females and half males) from Berkeley and San Francisco through posted announcements and snowball sampling method. Most subjects were college students. The subjects were divided into four groups, A-D, corresponding to four sets of acquisition devices. The ID number in Table 1 refers to different subjects in each group. However, six of them did not complete the entire experiment that required participation for two weeks. Therefore, the final data-analysis has only considered 14 subjects (6 females and 8 males). Table 1 shows the detailed anthropometrics of the subjects.

Table 1. Anthropometrics of subjects in this study

ID	Sex	Age	Height (m)	Weight (kg)	BMI*	Sensitivity to thermal environment†	Participation time
A1	Male	26	1.71	68	23.3	3.7	Nov. 28th - Dec. 12th, 2016
A2	Male	25	1.85	86	25.1	2.9	Apr. 2nd - 23th, 2017
A4	Male	31	1.7	55	19.0	3.5	May 1st - 19th, 2017
A5	Female	38	1.63	54	20.3	2	May 23rd - Jun. 6th, 2017
B1	Male	24	1.73	52	17.4	3.5	Oct. 17th - Nov.10th, 2016
B3	Female	28	1.73	86	28.7	3	Dec. 5th - 20th, 2016
B6	Female	25	1.8	57	17.6	3.1	Apr. 5th - 23rd, 2017
B8	Male	23	1.75	57	18.6	4	Apr. 30th - May, 17th, 2017
B9	Male	21	1.81	73	22.3	3	May 19th - Jun. 8th, 2017
C1	Female	48	1.63	57	21.5	3.7	Mar. 21st - Apr. 17th, 2017
C3	Female	20	1.65	52	19.1	2.5	May 14th - Jun. 28th, 2017
D1	Male	21	1.75	61	19.9	3	Dec. 2nd - 19th, 2016
D2	Male	32	1.8	70	21.6	3	Apr. 23rd - May 8th, 2017
D3	Female	22	1.58	56	22.4	3	May 13th - Jun. 1st, 2017

*BMI: Body mass index = Weight/Height^2

† Sensitivity to thermal environment from a survey question (Please indicate how sensitive you think you are to thermal conditions): Much lower sensitivity (0); Much higher sensitivity (5).

2.2. Questionnaires

Subjects took an online survey developed on Qualtrics using a cell phone to report their "right-now" thermal comfort. To reduce fatigue due to survey taking, subjects answered only three questions each time: 1) location (indoor or outdoor); 2) thermal sensation (continuous ASHRAE thermal sensation scale from cold <-3> to hot <3>); and 3) thermal preference (warmer, no change and cooler). The questions were randomly displayed on the survey platform (Figure 2).

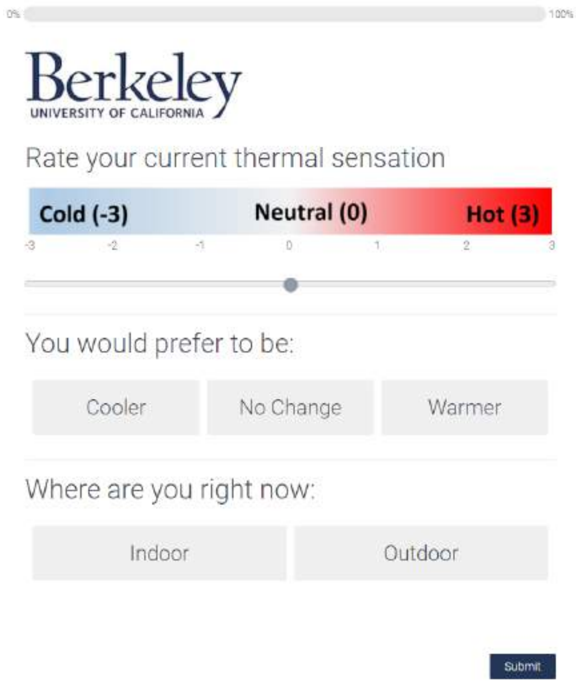


Figure 2. Online survey platform using Qualtrics

2.3. Wearable sensors

All the sensors are commercial and available on the market. The sensors were selected based on three criteria: 1) accuracy; 2) raw data access for research support; and 3) convenience to wear for 24/7. Despite that commercial wrist-bands and smart watches are easily accessible and user-friendly, the accuracy or capacity of research support fail to meet the requirements of this study. As such, all the sensors in this study were validated to generate data with accuracies of research purposes according to literature (Gillinov et al., 2017; van Marken Lichtenbelt et al., 2006; Mourcou et al., 2015). For instance, Basis Peak (Intel, Corp., U.S.) and Fitbit Charge HR (Fitbit, Inc., U.S.) inaccurately measure heart rate during exercise (Wang et al., 2017). As such, we applied Polar H7 strap (Polar Electro, Ltd., Finland) to monitor heart rate every second because of the high validity compared to ECG (Cheatham et al., 2015). Additionally, since subjects wore sensors for almost 24/7, two of the authors participated in a preliminary study for approximately two weeks to ensure that the selected sensors meet the criteria in the timeframe of participation.

Table 2 and Figure 3 describe the specification of the sensors and the wearing locations, respectively. Skin temperature at wrist and ankle was measured every minute by an iButton sensor (van Marken Lichtenbelt et al., 2006; Smith et al., 2010). In addition, we attached one iButton (Maxim Integrated Products, Inc., U.S.) sensor with the sensing side facing outside to a pin-badge to measure every minute the air temperature in the body proximity in order to capture transitions between different thermal environments. The badge was pinned at the lower pant (Figure 2) to reduce the influence of body thermal plume. Subjects took off pants with the sensor badge before sleep. The measured data represented air temperature where pants were located during sleep. A small-size cell-phone (POSH Mobile, Ltd., U.S.) in a wrist pocket measured accelerometer data to represent activity levels. The sample frequency was greater than 5 Hz, depending on the intensity of movement. Moreover, the cell-phone wirelessly uploaded heart rate data to the cloud.

Table 2. Sensors to measure physiological data

Model	Accuracy	Parameter measurement
iButton- Maxim integrated DS 1923 (Maxim Integrated Products, Inc., U.S.)	± 0.2 °C after calibration	Skin temperature and air temperature close to the body
Polar H7 Bluetooth Smart Heart Rate Sensor (Polar Electro, Ltd., Finland)	Concordance correlation coefficient, 0.99 (Wang et al. 2017)	Heart rate
Cell phone POSH built app Micro X S240 (POSH Mobile, Ltd., U.S.)	Not applicable	Accelerometer data to represent metabolic rates. Server to receive heart rate data

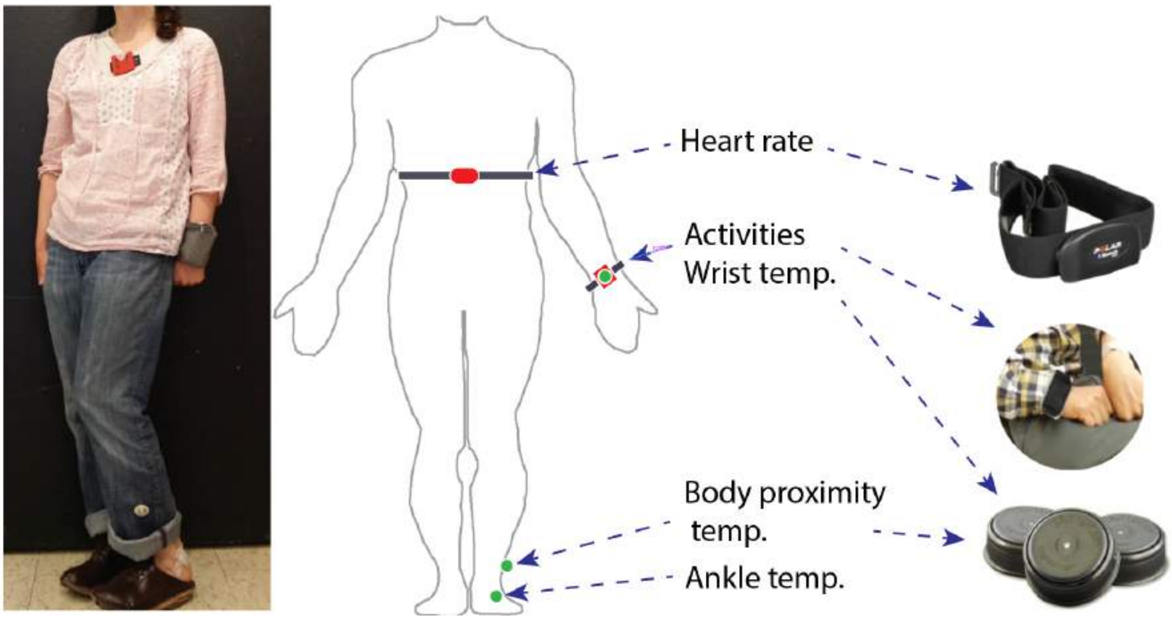


Figure 3. Sensors and wearing locations.

2.4. Procedure for data collection

Before participation, each subject had a one-hour training on the study procedure. The subjects were also asked to wear the sensors during the train to ensure that they were comfortable with them. A signed consent form approved by the institutional review board of University of California, Berkeley (CPHS #2016-09-9129) was obtained from each subject.

The subjects wore all the sensors for at least 20 hr and took the survey (Figure 2) for at least 12 times per day. The total duration of the participation was 14 days. We encouraged subjects to take the survey as many times as possible, especially when their thermal conditions and preferences altered, such as after working out or moving to a different thermal environment. The subjects received a text reminder to take the survey. Each subject was compensated with $350 (or more if taking more surveys) after the entire participation.

Table 2. Parameters and features for the development of personal thermal comfort models

Parameters	Features
Skin temperature at ankle and wrist	Temperature gradient over 15 min before a vote
	Average temperature over 15 min before a vote
	Temperature gradient over 60 min before a vote
	Average temperature over 60 min before a vote
	Temperature difference between daily average and 15 min average before a vote
	Average skin temperature difference between wrist and ankle over 15 min before a vote
	Difference between daily average outdoor and skin temperature averaged over 15 min before a vote
Body proximity temperature	Temperature gradient over 15 min before a vote
	Average temperature over 15 min before a vote
	Temperature gradient over 60 min before a vote
	Average temperature over 60 min before a vote
	Temperature difference between daily average and 15 min average before a vote
	Difference between daily average outdoor and body proximity temperature averaged over 15 min before a vote
Heart rate	Difference between daily and 15 min average before a vote
	Difference between daily and 60 min average before a vote
Metabolism	Variation of accelerometer data over 15 min before a vote
	Variation of accelerometer data over 60 min before a vote
Location	Indoor or outdoor
Time	Morning (0 - 12:00), afternoon (12:00 - 18:00), or evening (18:00 - 24:00)
Weather	Average outdoor temperature, humidity, wind, and precipitation over 60 min before a vote

2.5. Machine learning algorithm and feature selection

Among the three surveyed questions (Figure 2), thermal preference is the most relevant parameter to HVAC system control because it explicitly describes which action the HVAC should take. This study aims to apply classification algorithms to develop a thermal comfort model for each subject to infer their thermal preference.

Random Forest (RF) constructs a multitude of individual decision trees and predict mean outcomes from the average results of all the trees (Breiman, 2001). This technique, also known as "bagging", is particularly powerful in the small data regime, because it effectively generates an "artificial" dataset for each individual learner based only on the limited available data (Breiman, 1996). Random Forest has been successfully applied for thermal preference classification (Huang et al., 2015).

The features for model training consisted of physiological data, body-proximity temperature, weather (wind, solar radiation, temperature, humidity), location and time (Table 2). The derivatives (e.g., gradients and standard deviation) of the measured data were also considered. For instance, the negative gradient of skin temperatures of the extremities represented the drop of skin temperature, possibly indicating a cool thermal sensation (Wang et al., 2007).

3. Results and Discussion

3.1. Thermal sensation and preference

The overall thermal sensation and preference of each unique subject are shown in Figure 4. The vote number during the entire participation was 275 ± 77 (mean ± standard deviation). Most of the thermal sensation votes (interquartile range) were between slightly cool and slightly warm. The mean thermal sensation for all subjects is close to neutrality (mean ± standard deviation: 0.06 ± 0.75). However, thermal sensation ranges are significantly different among subjects. For instance, the thermal sensation range of subject B1 (0.44 ± 1.16) was much smaller compared to subject B8 (0.33 ± 0.05).

The subjects in this study preferred changing their thermal environment for about 30% (min = 21% and max = 88%) of the participation period, which suggests a strong demand for a personalized thermal comfort.

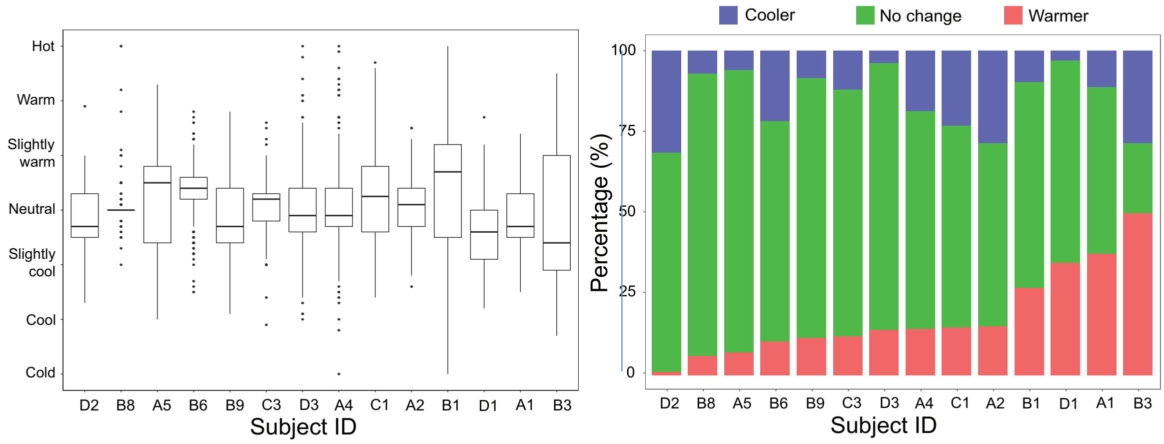


Figure 4. Thermal sensation and preference for each subject

3.2. Thermal preference prediction

We trained a personal comfort model with thermal preference as the dependent for each subject. Table 3 summaries the overall classification of warmer, no change and cooler. The accuracy was calculated as the chance (in percentage) of predicting a thermal vote correctly. The average accuracy of all the subjects is 74 ± 13% (mean ± standard deviation) for the field experiments. It is worthy to notice that the accuracy increase with the increase of the data size, above 300 votes, the accuracy is on average 80%. The differences in the accuracies imply that the dominant features to predict thermal preference might be different for each subject. A further investigation on the contribution of each feature to the prediction accuracy is underway.

Table 3. Overall classification of warmer (W), no change (NC) and cooler (C) for each subject

ID	Data size	True preference: Warmer			True preference: No change			True preference: Cooler			Overall accuracy (%)
		W*	NC*	C*	W*	NC*	C*	W*	NC*	C*	
A1	152	**28**	29	0	27	**51**	0	5	10	**2**	53
B3	242	**98**	8	15	41	**8**	3	40	3	**26**	55
A2	253	**2**	36	0	1	**126**	16	0	54	**18**	58
D1	156	**15**	37	0	13	**86**	0	0	3	**2**	66
C1	256	**11**	26	1	12	**136**	11	2	34	**23**	66
B1	271	**16**	57	0	9	**160**	3	1	18	**7**	68
B6	393	**2**	39	0	0	**264**	3	0	77	**8**	70
B9	261	**10**	20	0	9	**197**	3	0	19	**3**	81
C3	399	**14**	34	0	5	**295**	3	0	35	**13**	81
D2	198	**0**	2	0	0	**129**	5	0	24	**38**	84
A5	270	**0**	19	0	1	**232**	2	0	16	**0**	86
D3	322	**12**	33	0	0	**265**	0	0	9	**3**	87
A4	323	**13**	28	5	2	**215**	0	1	1	**58**	89
B8	353	**9**	12	0	2	**304**	1	0	9	**16**	93

*Predicted thermal preference: Warmer (W); No change (NC); Cooler (C)

In this study, the thermal comfort learning method based on Random Forest requires the collection of a sufficiently large labelled dataset for representation of common scenarios and generalization to unknown situations. This poses a practical challenge, because people may be reluctant to report their thermal comfort due to weariness. The authors will be developing data-efficient algorithms that alleviate this stringent requirement. One promising direction is to train the classifiers with high-level heuristic rules rather than low-level labels, a form known as "weak supervision" (Jin, 2017). The idea has been applied to occupancy detection based on smart meter data by leveraging common work schedules (Jin et al., 2017). Similarly, for thermal comfort, heuristics such as "I typically feel cold at night" or "I usually feel hot after running" can be readily encoded into noisy estimates of thermal comfort labels to initiate weakly supervised learning. This can potentially enable large-scale deployment of the proposed method of thermal comfort sensing.

4. Conclusions

We used wearable sensors to track real-time physiological signals and environmental data for almost 24/7 for each subject. The collected information was trained by a Random Forest algorithm to develop personal thermal comfort model. The subjects' perceived thermal comfort was also recorded as ground true for the model development and validation. We are able to predict personal thermal preference with an average accuracy of 75% (53 - 93%) based on physiological signals (skin temperatures at wrist and ankle, heart rates, and activity levels) and environmental data. The results imply that wearable sensors can be suitable tools to infer thermal comfort in the free-living environment. In the future, we will explore more features from the sample data and more robust algorithms to reduce the requirement of survey inputs during the training period.

5. References

Abdallah, M., Clevenger, C., Vu, T., and Nguyen, A., 2016. Sensing occupant comfort using wearable technologies. In: *Construction Research Congress 2016*. San Juan, Puerto Rico, May 31- June 2, 2016. American Society of Civil Engineers.

Barrios, L., and Kleiminger, W., 2017. The Comfstat - automatically sensing thermal comfort for smart thermostats. In: *Proceedings of the IEEE International Conference on Pervasive Computing and Communications*. Kona, HI, USA., Mar.13 - 17, 2017. IEEE.

Breiman, L., 1996. Bagging predictors. *Machine Learning,* 24, pp 123 - 140.

Breiman, L., 2001. Random Forests. *Machine Learning,* 45, pp 5 - 32.

Chaudhuri, T., Zhai, D., Soh, Y.C., Li, H., and Xie, L., 2018. Random forest based thermal comfort prediction from gender-specific physiological parameters using wearable sensing technology. *Energy and Buildings,* 166, pp 391 - 406.

Cheatham, S.W., Kolber, M.J., and Ernst, M.P., 2015. Concurrent validity of resting pulse-rate measurements: a comparison of 2 smartphone applications, the polar H7 belt monitor, and a pulse oximeter with Bluetooth. *Journal of Sport Rehabilitation,* 24, pp 171 - 178.

Cheung, C.T., Schiavon, S., Gall, E., Jin M., and Nazaroff, WW., 2017. Longitudinal assessment of thermal and perceived air quality acceptability in relation to temperature, humidity, and CO2 exposure in Singapore. *Building and Environment,* 115, pp 80 - 90.

Choi, J.H., and Loftness, V., 2012. Investigation of human body skin temperatures as a bio-signal to indicate overall thermal sensations. *Building and Environment,* 58, 258 - 269.

Choi, J.H., Loftness, V., and Lee, D.W., 2012. Investigation of the possibility of the use of heart rate as a human factor for thermal sensation models. *Building and Environment,* 50, 165 - 175.

Erickson, V.L., and Cerpa, A.E., 2012. Thermovote: Participatory Sensing for Efficient Building HVAC Conditioning. In: *Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, Toronto, Ontario, Canada, November 20 - 22 2012. New York: ACM.

Ghahramani, A., Tang, C., and Becerik-Gerber, B., 2015. An online learning approach for quantifying personalized thermal comfort via adaptive stochastic modeling. *Building and Environment,* 92, 86 - 96.

Ghahramani, A., Castro, G., Becerik-Gerber, B., and Yu, X., 2016. Infrared thermography of human face for monitoring thermoregulation performance and estimating personal thermal comfort. *Building and Environment,* 109, pp 1 - 11.

Gillinov, S., Etiwy, M., Wang, R., Blackburn, G., Phelan, D., Gillinov, A.M., Houghtaling, P., Javadikasgari, H., and Desai, M.Y., 2017. Variable Accuracy of Wearable Heart Rate Monitors during Aerobic Exercise. *Medicine and Science in Sports and Exercise,* 49, pp 1697 - 1703.

Hang-yat, L.A., and Wang, D., 2013. Carrying my environment with me: A participatory-sensing approach to enhance thermal comfort. In: *Proceedings of the Fifth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, Roma, Italy, November 11 - 15, 2013. New York: ACM.

Huang, C.C., Yang, R., and Newman, M.W., 2015. The Potential and Challenges of Inferring Thermal Comfort at Home Using Commodity Sensors. In: *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. Osaka, Japan, 7 - 11 September 2015. New York: ACM.

Humphreys, M.A., and Fergus Nicol, J., 2002. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy and Buildings,* 34, pp 667 - 684.

Jin, M., 2017. *Data-efficient analytics for optimal human-cyber-physical systems.* Ph.D. University of California, Berkeley.

Jin, M., Jia, R., and Spanos, C.J., 2017. Virtual Occupancy Sensing: Using Smart Meters to Indicate Your Presence. *IEEE Transactions on Mobile Computing,* 16, pp 3264 - 3277.

Karmann C, Schiavon S, Arens E. 2018. Percentage of commercial buildings showing at least 80% occupant satisfied with their thermal comfort. In: *Proceedings of the 10th Windsor Conference*, Windsor, UK. April 12 - 15, 2018.

Kim, J., Zhou, Y., Schiavon, S., Raftery, P., and Brager, G., 2018a. Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning. *Building and Environment,* 129, pp 96 - 106.

Kim, J., Schiavon, S. and Brager, G., 2018b. Personal comfort models – a new paradigm in thermal comfort for occupant-centric environmental control. *Building and Environment,* accepted.

Li, D., Menassa, C.C., and Kamat, V.R., 2017. Personalized human comfort in indoor building environments under diverse conditioning modes. *Building and Environment,* 126, 304 - 317.

van Marken Lichtenbelt, W.D., Daanen, H.A.M., Wouters, L., Fronczek, R., Raymann, R.J.E.M., Severens, N.M.W., and Van Someren, E.J.W., 2006. Evaluation of wireless determination of skin temperature using iButtons. *Physiology and Behavior,* 88, pp 489 - 497.

McCartney, K., and Humphreys, M. 2002. Thermal comfort and productivity. In: *Proceedings of the 9th International conference on indoor air quality and climate.* Monterey, California, 30 June - 5 July 2002. International society of indoor air quality and climate.

Mourcou, Q., Fleury, A., Franco, C., Klopcic, F., and Vuillerme, N., 2015. Performance Evaluation of Smartphone Inertial Sensors Measurement for Range of Motion. *Sensors,* 15, pp 23168 - 23187.

Nguyen, T.A., and Aiello, M., 2013. Energy intelligent buildings based on user activity: A survey. *Energy and Buildings,* 56, pp 244 - 257.

Nouvel, R., and Alessi, F., 2012. A novel personalized thermal comfort control, responding to user sensation feedbacks. *Building Simulation*, 5, 191 - 202.

Purdon, S., Kusy, B., Jurdak, R., and Challen, G., 2013. Model-free HVAC control using occupant feedback. In: *Proceedings of the 38th annual IEEE conference on local computer networks: LCN Workshops.* Sydney, Australia, 21 - 24 October 2013, IEEE.

Ranjan, J., and Scott, J., 2016. ThermalSense: Determining dynamic thermal comfort preferences using thermographic imaging. In: *Proceedings of the ACM International Joint Conference on Pervasive and Ubiquitous Computing*, Heidelberg, Germany, 12 - 16 September 2016. New York: ACM.

Sarkar, C., Nambi, S.A.U., and Prasad, R.V., 2016. iLTC: Achieving individual comfort in shared spaces. In: *Proceedings of the 2016 International Conference on Embedded Wireless Systems and Networks.* Graz, Austria, 15 - 17 February 2016, Canada: Junction publishing.

Shen, Y., Zheng, J., Zhang, Z., and Li, C., 2012. Design and implementation of a wearable, multiparameter physiological monitoring system for the study of human heat stress, cold stress, and thermal comfort. *Instrumentation Science and Technology*, 40, 290 - 304.

Sim, S.Y., Koh, M.J., Joo, K.M., Noh, S., Park, S., Kim, Y.H., and Park, K.S., 2016. Estimation of Thermal Sensation Based on Wrist Skin Temperatures. *Sensors*, 16, 420.

Smith, A.D.H., Crabtree, D.R., Bilzon, J.L.J., and Walsh, N.P., 2010. The validity of wireless iButtons® and thermistors for human skin temperature measurement. *Physiological Measurement,* 31, 95.

Sugimoto, C., 2013. Human sensing using wearable wireless sensors for smart environments. In: *Proceedings of 2013 Seventh International Conference on Sensing Technology (ICST)*, Wellington, New Zealand, 3 - 5 December 2013, IEEE.

Wang, D., Zhang, H., Arens, E., and Huizenga, C., 2007. Observations of upper-extremity skin temperature and corresponding overall-body thermal sensations and comfort. *Building and Environment,* 42(12), pp 3933 - 3943.

Wang, R., Blackburn, G., Desai, M., Phelan, D., Gillinov, L., Houghtaling, P., and Gillinov, M., 2017. Accuracy of Wrist-Worn Heart Rate Monitors. *JAMA Cardiology,* 2, pp 104–106.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Developing Personal Thermal Comfort Models for the Control of HVAC in Cars Using Field Data

Umberto Fugiglando[1], Daniele Santucci[1,2], Iva Bojic[1,3], Paolo Santi[1,4], Toby Chin To Cheung [5], Stefano Schiavon[6] and Carlo Ratti[1]

[1] Senseable City Laboratory, Massachusetts Institute of Technology, Cambridge MA, USA
[2] Chair of Building Technology and Climate Responsive Design, Technische Universität München, Munich, Germany
[3] Senseable City Lab, Singapore-MIT Alliance for Research and Technology, Singapore
[4] Istituto di Informatica e Telematica del CNR, Pisa, Italy
[5] Berkeley Education Alliance for Research in Singapore, Singapore
[6] Center for the Built Environment, University of California, Berkeley, CA, USA

Abstract: Personal comfort models predict an individual's thermal comfort instead of the average response for a large population. We attempted to develop personal comfort models for car drivers using data collected from 10 cars while driving for approximately 2,000 hr. We measured conditions collected by the CAN-bus (Controller Area Network), a data acquisition system that is present in most of the modern cars. Data includes information about the in-vehicle thermal conditions, the surrounding environment, the status of the Heating, Ventilation, and Air Conditioning (HVAC) system, and the behavior of the occupant. The objective of the study is to assess the feasibility of inferring occupant's thermal preference from the data available already available in most cars. By selecting and filtering all the available signals that are relevant for comfort, in this study we map the user actions of turning on/off their seat heating and correlate them to the vehicle indoor and outdoor conditions. The presented study provides the basis for using a machine learning automated process for thermal self-regulating HVAC system with the aim to improve comfort conditions and safety.

Keywords: Thermal comfort, Personal comfort model, Machine learning, User behavior, Personal comfort systems.

1. Introduction

Reaching satisfactory thermal comfort conditions in cars is a complex subjective process that may requires many adjustments. The continuously changing environment that a moving vehicle is encountering and the fluctuating outdoor conditions cause inhomogeneous and highly dynamic indoor conditions. The thermal regulation systems implemented in cars is often controlled only on air temperature and it may require several control actions from the driver and passengers. Automatic climate control systems are often ineffective in providing satisfying comfort levels. Those systems are usually force air systems making them highly instable in a continuously changing environment (Hausladen et al. 2004). Moreover, thermal comfort cannot be evaluated and achieved only in terms of temperature control, as it is influenced by other parameters such as radiant heat, metabolic rate, airspeed, and clothing insulation (Kim et al., 2018a and b).

While comfort conditions in buildings have been a widely explored topic, thermal comfort in cars has encountered growing interest, particularly in relation to problems of asymmetric conditions and in the context of electric mobility due to the high impact of conditioning system on the battery autonomy (Mebarki et al., 2014; Zhang et al., 2014; Fiori et al. 2016). In addition, modelling radiation and energy fluxes in a vehicle that moves through varying weather conditions requires the computation of a high number of variables, making the simulation models very complex.

To avoid the complex modelling, the present study focuses on the relationship between the user behavior and thermal conditions. Pervasive collection and analysis of car sensory data is made possible through the CAN-bus (Controller Area Network) (Kiencke et al., 1986) technology that provides almost real-time information about the car, the driver and the surrounding environment. Each modern car, in fact, contains more than 2,000 sensors constantly producing data that open up the possibility to capture some of it to map user behavior and the thermal environment with a high resolution.

Personal comfort models are built from analyses derived from such data and designed to predict an individual's thermal comfort response, instead of extrapolating related assumptions derived from the average response of a large population (Kim et al. 2018b). They have a much higher predicting power than PMV and adaptive personal comfort models can be based on environmental parameters (e.g., air temperature) (Cheung et al., 2017), occupant feedback and behaviour (Kim et al. 2018a), occupant behaviour and measured physiological parameters (e.g., skin temperature, heart rate) (Liu et al. 2018).

Currently, comfort is typically achieved in cars as a result of occupants adjusting internal thermostats as conditions change. The present study aims at assessing the feasibility of developing personal comfort models based on CAN-bus signals, particularly concentrating on the seat heat. If successful, this approach would allow for a personalized automated thermal control in vehicles designed to improve comfort conditions and safety, automating HVAC adjustments basing on a high number of environmental control variables.

2. Methodology

CAN-bus technology is a standard bus that allows fast and reliable communications among all electronic components in cars. The possibility of leveraging the CAN-bus technology to couple human and environmental sensed data for predicting and studying human behavior has been proposed and analyzed for several applications (Massaro et al., 2017). With the aim of developing a personal comfort model based on CAN-bus signals, this study was based on the use of selected signals generated by actions that the user undertakes in order to influence thermal comfort conditions.

Personal models, traditionally, are based on the PMV model (Predicted Mean Vote) (Fanger et al., 1970) that requires six layers of information: air temperature, mean radiant temperature, relative humidity, air speed, clothing factor and metabolic rate. Figure 1 gives a chart that synthetizes the functioning of the model. The PMV model is a steady state model, therefore it does not consider the dynamics of the phenomenon. Furthermore, the implementation of the PMV model requires high accuracy in the input variables that are strongly related to the users, such as clothing insulation and metabolic rate, which are therefore assumed or simplified and cannot be updated to reflect the actual comfort conditions of individuals in a complex setting (Kim et al., 2018a).

The proposed model considers as input variables a subset of the CAN-bus data, which can be divided in three categories: user's actions on the HVAC system; user actions on car components that influence the personal comfort (such as windows and shades); other environmental variables (such as temperature).

The drivers did not answer to thermal comfort surveys, therefore, thermal comfort was inferred from their actions. We recognize that this is a limitation. The basic principle that we assumed is considering user actions as moments in which thermal comfort is not achieved, and thus actions are triggered in order to change the car's climate condition. Therefore, analyzing those actions and the corresponding environmental variables (

Figure 1) – including the evolution of the variables up to the action's moment – personal patterns in terms of comfort achievement could be inferred. Basing upon those patterns, the model can be used with a predictive approach, predicting the next user action given historical actions and environmental variables (Figure).

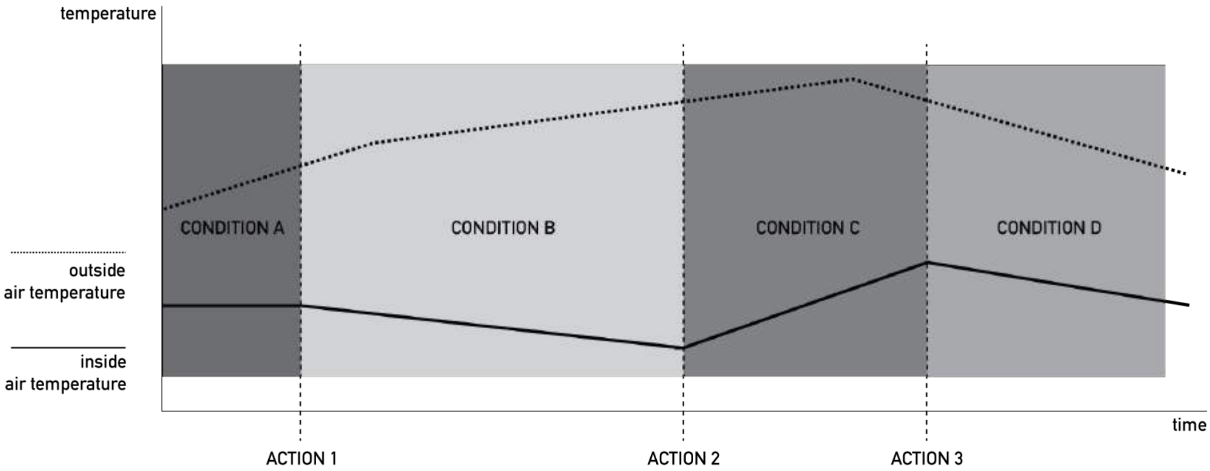


Figure 1 – Example of user actions and environmental variables change.

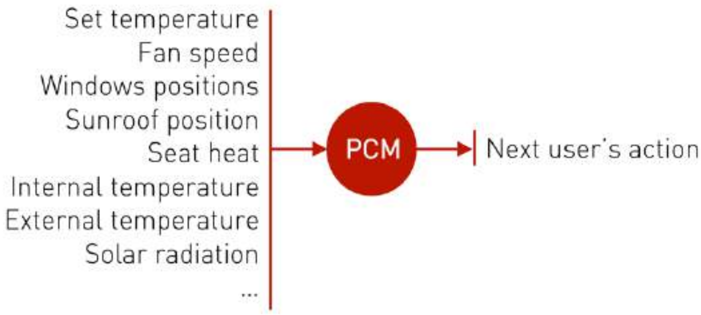


Figure 2 – Structure of a Personal Comfort Model (PCM)

In particular, the proposed personal comfort model – which boils down to a machine learning predictive algorithm – is composed of two phases (Figure). The first is an initial training phase, where user actions are monitored and rules and non-linear relations are inferred. The second is an *autonomous real-time phase*, where rules learnt in the first phase are applied to external variables in order to predict the user actions and, ultimately, change HVAC settings accordingly.

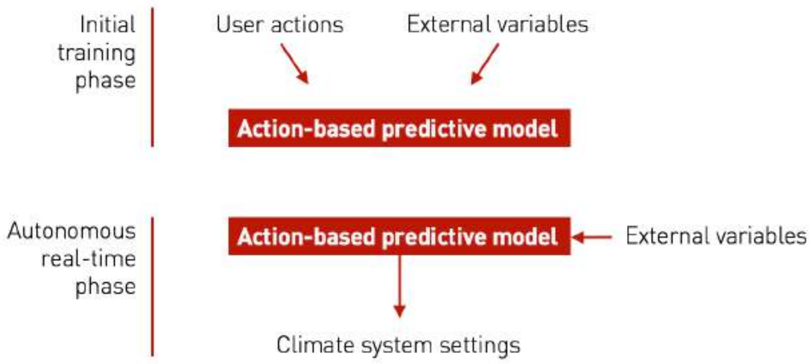


Figure 3 – Conceptual phases of the PCM machine learning model.

3. Dataset

3.1. Experimental settings

The data acquisition took place in 2014 by Audi AG and Audi Electronics Venture in Ingolstadt, Germany. 10 different cars have been retrofitted with a data-logger and more than 2,000 CAN-signals have been recorded. A total number of 53 drivers have been involved in the data collection, providing a rich dataset of more than 2,135 hours of driving over 55 d of experiments. No personal information about the drivers has been recorded.

Cars were picked up by the drivers in a central deposit and had to be returned within the same day. Each time a user switched on the car engine, the computer registered a new session. A total of 1,987 sessions were recorded; each user drove an average of 31 sessions, with an average duration of 64 minutes per session. Figure 1 plots the durations of sessions for each driver. Data has been recorded for 55 days in the months of March, April and May 2014 during weekdays. Figure 2 shows the temporal distribution of data acquisitions for each car. Meteorological conditions were various during the experiment, with several days of rain and external temperatures ranging between -3 and 24 °C[1].

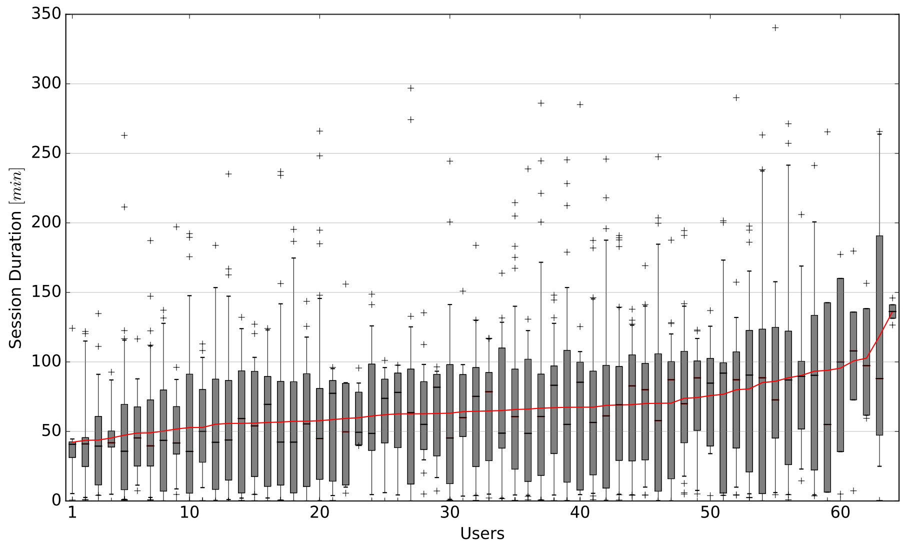


Figure 1 – Sessions duration for each user, sorted by their mean value (red line).

[1] Data retrieved from Weather Underground, https://www.wunderground.com, station IBAYERNIK12.

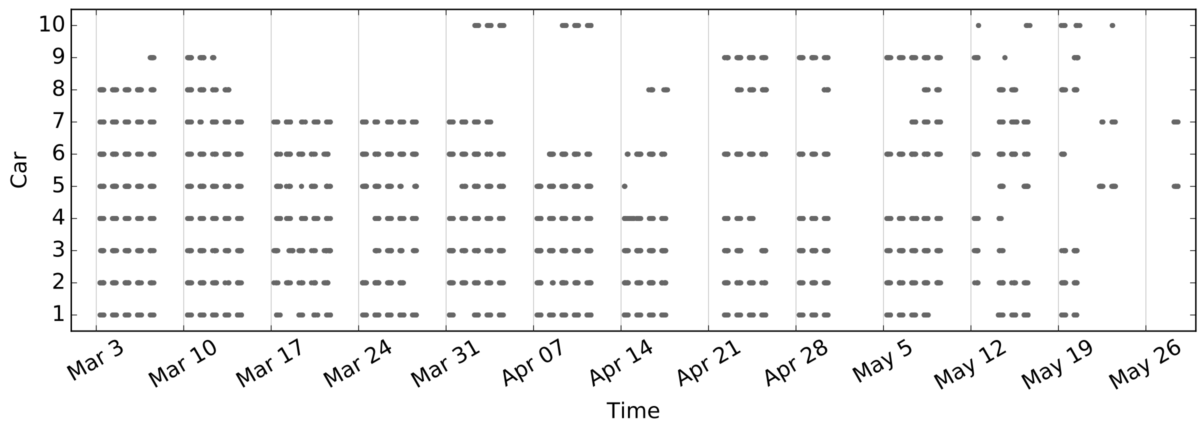


Figure 2 – Sessions distribution over time for each car.

3.2. Data structure, filtering and preprocessing

The database contains the complete set of signals form the CAN-bus, a wide spectrum of information that tracks different communications among components in the vehicle and for different purposes. A summary of the high-level information available in the CAN-bus useful for a climate comfort model can be found in Table 1. For windows statuses, we had information about both driver's and passenger's window being opened or closed. Moreover, we had records whether it is raining and also what is the wiper speed. The position of the sunroof blind is telling us whether it is sunny or not. Finally, in this study we only focused on user action of turning on/off driver's seat heat.

Table 1 – List of used signals in the study.

Signal information	**Taxonomy area**	**Data type**	**Raw table cardinality**
Driver's window opened	Windows and shades	Boolean	10,462
Passenger's window opened	Windows and shades	Boolean	6,700
Sunroof blind stage	Windows and shades	Boolean	5,200
Windshield wiper active	Rain	Boolean	18,488
HVAC system on/off	HVAC	Boolean	25,700
AC compressor on/off	HVAC	Boolean	7,355
Driver’s seats heat levels	HVAC	integer	6,707
Internal temperature	Environment	float	250,641
External temperature	Environment	float	116,935

The datatype of the signals recorded is Boolean (i.e. on/off), integer or float, and their sizes vary from a few MB to a few GB for each sensor. The signals are not uniformly sampled, i.e. the time difference between each sample of the physical quantity is not constant. This is due to the nature of the sensor system that was designed to sample the quantity only if there were a minimal variation with respect to the previous sampled value. In this way, the size of the database does not increase linearly with time and disk space is optimized.

We preprocessed the data after we retrieved the raw data from the database. Although it was said that the record of sampling was saved only if there was a minimal variation with respect to the previous sampled value, the dataset contained consecutive records with the same values, which had to be filtered first. Outlier filtering was also performed on the internal temperature signal, as very often the initial value when a new session would start was -40 °C degrees.

The focus in this paper is on user action of turning on/off their seat heat; therefore, we produced a histogram of the values (Figure). The dataset contained 50 records (about 1.5%) with values larger than 120 min, 30% of values that change under 1 min and 42% of values that changes under 3 min. We decided to omit all records that changed under 3 min, which left us in total with 2,320 records of user's actions.

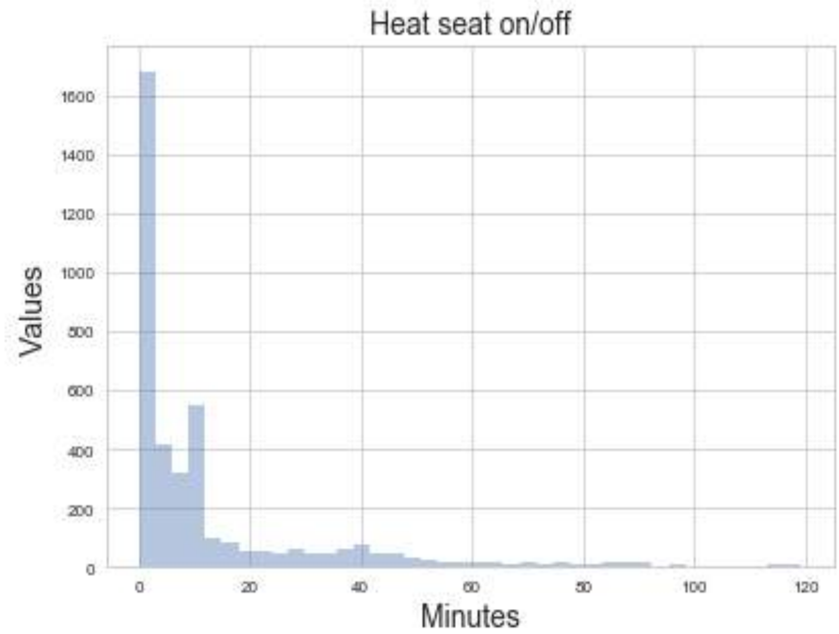


Figure 6 – Histogram showing how often user action of turning on/off seat heat is occurring.

After cleaning the dataset, we performed the last step of preprocessing in which we overlaid user action of turning on/off seat heat with the aforementioned vehicle indoor and outdoor conditions. As previously mentioned, as signals were not collected synchronously, for each user action we had to find the closest match in other tables, i.e. the record that occurred in approximately the same time window. However, we did not include values that were too much apart from each other, so we used a threshold of three minutes. This means that we would add to the specific user action of turning on/off their seat heating the corresponding value from other tables only if the record in the second table was made either three minutes before the user action or after, otherwise we would dismiss both records from our further analysis. Finally, if we would find more than one value in the second table within three minutes before/after the user action, we would take the one that was made at time that was closer to the time of the original user action.

4. Analysis

In order to determine possible recurrent co-occurrence relationships among different signals, a first analysis was carried out to determine the correlation between pairs of samples. The analysis concentrated on all couples formed by the internal temperature, the external temperature and the driver's seat in association with other signals, namely HVAC system status, AC compressor status, driver's and passenger's windows, windshield wiper. The correlation is expressed using the Pearson's correlation coefficient, ranging from -1 to 1. The complete list of the analyses results is reported in Table 2.

Table 2 – Correlation coefficients between driver's seat heating and other signals.

Signal 1	**Signal 2**	**Correlation coefficient***
Internal temperature	HVAC system on/off	**0.10**
	AC compressor on/off	**0.12**
	Driver's window position (open/closed)	0.01
	Passenger's window position (open/closed)	-0.05
	Windshield wiper	-0.08
External temperature	HVAC system on/off	0.04
	AC compressor on/off	0.09
	Driver's window position (open/closed)	-0.03
	Passenger's window position (open/closed)	**-0.10**
	Windshield wiper	-0.02
Driver's seat heating	HVAC system on/off	**0.42**
	AC compressor on/off	**0.46**
	Internal temperature	-0.04
	External temperature	-0.06
	Driver's window position (open/closed)	**-0.21**
	Passenger's window position (open/closed)	**-0.21**
	Windshield wiper	**0.36**

* Correlation coefficients above 0.1 are bolded

Results show higher correlations of the driver's seat heating with the HVAC system status, the AC compressor status and the windshield wiper. This means that high values of seat heat usually correspond to HVAC, AC in heating mode and wipers status on. A slightly weaker correlation occurs between the driver's seat heating and the window positions (not surprisingly, negative correlations, i.e. if the seat heat level is high the window is closed, and vice versa), while there are no significant correlations among other signals.

A further investigation has been carried out to visually inspect the variability of non-categorical variables (internal and external temperature) with the driver's seat heating level. In Figure 73, boxplots confirm the non-correlation between the seat heating level and internal or external temperature; for this reason, these variables cannot be used to control the car heating system

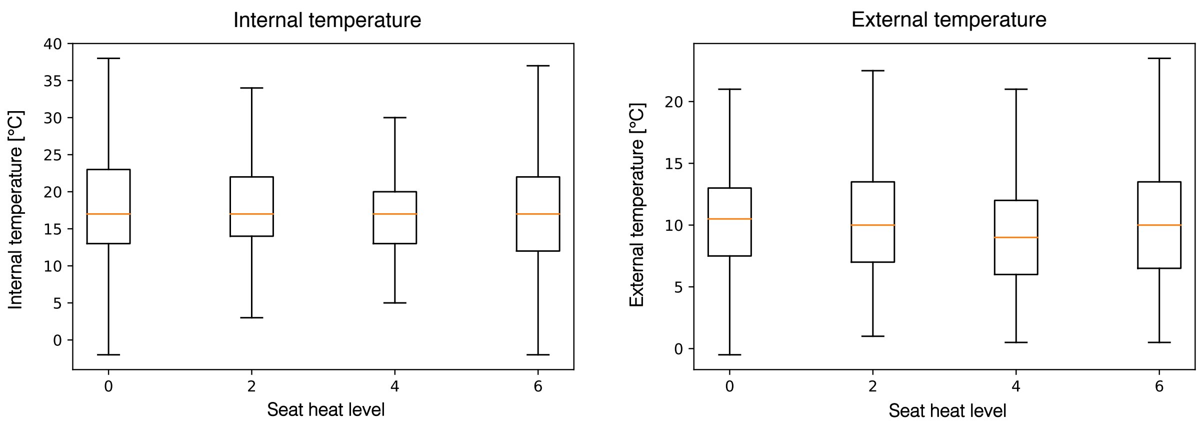


Figure 73 – Internal and external temperatures distributions for different levels of driver's seat heating.

Basing on the promising correlation results, more sophisticated models are needed in order to investigate possible non-linear relations between signals and user actions. Suitable machine learning methods could be Artificial Neural Networks (ANN), Support Vector Machines (SVM), regression trees or random forest models (Hastie et al., 2009). In this work, considering the preliminary exploration phase of the database, experimental data were analyzed using a regression tree model.

Following the scheme explained in Figure , the model has been trained with vectors containing values of the variables in Table 1, except for the seat heating that was considered as the label object of inference. For simplicity, the seat heat level was considered as a Boolean variable, mapping the value 0 to *false* and 2, 4, 6 to *true*.

The model implemented did not show satisfactory results (R^2 close to zero). This is due to a combination of different factors, such as: the high number of missing values among the matched signals, as mentioned in the preprocessing paragraph; the low amount of datapoints in the database; the low variability in overall weather conditions and user's perception due to the middle-season months in which the experiment has been carried out (March-May), the fact that people on the cars for the first time might have unintentionally pressed on some controls. Overall the data set, although apparently valuable, proved to be not sufficiently comprehensive to establish statistically significant prediction relationships between the considered variables. Given this limitation, the authors are not confident in the model's results at the present stage and general conclusions cannot be drawn from this paper's specific implementation. We think that with a properly designed thermal comfort experiment and the presence of driver thermal comfort preference survey as ground true, it is possible to create personal and group comfort model with high predicting power.

5. Conclusions

This paper attempted to develop a personal comfort model to be applied for the control of HVAC in vehicle using real data collected from the CAN-bus. The personal comfort paradigm has been applied to in-vehicle comfort and an analysis of the signals that could be used for achieving this goal has been carried out. Moreover, a preliminary data analysis has been performed on experimental data, showing a good correlation between the seat heating and other signals; on the other hand, no significant correlation has been found between seat heating level and internal or external temperature. However, after the proposed model was implemented, we did not get satisfying results. Therefore, in future work, the presented model should be further tested with bigger dataset acquired in more various and extreme climatic conditions, occupant thermal preference should be collected and a fine-tuning of the model's parameters will be required in order to train it on more complex datasets.

6. Acknowledgements

The authors would like to thank Cisco, SNCF Gares & Connexions, Brose, Allianz, UBER, Fondation OCP, Liberty Mutual, Ericsson, Saudi Telecom, Volkswagen Group America, Philips, Austrian Institute of Technology, Fraunhofer Institute, Kuwait-MIT Center for Natural Resources, SMART—Singapore MIT Alliance for Research and Technology, SinBerBEST - Singapore-Berkeley Building Efficiency and Sustainability in the Tropics, AMS Institute Amsterdam, Victoria State Government, and all the members of the MIT Senseable City Lab Consortium for supporting this research. Special thanks go to the Institute of Advanced Studies of Technical University of Munich for supporting the research exchange.

7. References

Brusey, J., Hintea, D., Gaura, E., Beloe, N., 2017. Reinforcement learning-based thermal comfort control for vehicle cabins. *Mechatronics*, September 2017, pp. 1-21.

Cheung, T., Schiavon, S., Gall, E. T., Jin, M., and Nazaroff, W., 2017. Longitudinal Assessment of Thermal and Perceived Air Quality Acceptability in Relation to Temperature, Humidity, and CO2 Exposure in Singapore. *Building and Environment* 115, pp. 80-90.

Fiori, C., Ahn, K., Rakha, H.A., 2016. Power-based electric vehicle energy consumption model: Model development and validation. *Applied Energy*, 168, pp. 257-268.

Hastie, T., Tibshirani, R., and Friedman, J., 2009. *The Elements of Statistical Learning*. 2nd ed. Springer.

Hausladen, G., De Saldanha, M., Liedl, P., 2004. *ClimaDesign: Lösungen für Gebäude die mit weniger Technik mehr können*. München: George D.W. Callwey, 2004.

Hintea, D., Kemp, J., Brusey, J., Gaura, E., and Beloe, N., 2014. Applicability of Thermal Comfort Models to Car Cabin Environments. *Proceedings of the 11th International Conference on Informatics in Control, Automation and Robotics*, pp. 769-776.

Kiencke, U., Dais S., and Litschel M., 1986. Automotive Serial Controller Area Network. *SAE Technical Paper*.

Kim, J., Zhou, Y., Schiavon, S., Raftery, P., Brager, G., 2018. Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning. *Building and Environment,* 129, pp. 96-106.

Kim, J., Schiavon S., Brager, G., 2018. Personal comfort models – A new paradigm in thermal comfort for occupant-centric environmental control. *Building and Environment*. 10.1016/j.buildenv.2018.01.023

Liu, S., Jin, M., Das, H.P., Spanos, C.J., Schiavon S., 2018. Personal thermal comfort models based on physiological parameters measured by wearable sensors. *Proceedings of the 10th Windsor Conference*, Windsor, UK. April 12-15th.

Massaro, E., Ahn, C., Ratti, C., Santi, P., Stahlmann, R., Lamprecht, A., Roehder, M., and Huber, M., 2017. The Car as an Ambient Sensing Platform. *Proceedings of the IEEE*, 105(1), pp. 3-7.

Mebarki, B., Draoui, B., Allaoua, B., 2014. Investigation on Electric Air- Conditioning System Energy Consumption of an Electric Vehicle Powered by Li-ion Battery. *Advances in Automobile Engineering,* 108(3).

Rosenfeld, A., Azaria, A., Kraus, S., Goldman, C.V., and Tsimhoni, O., 2015. Adaptive advice in automobile climate control systems. *Proceedings of the 14th International Conference on Autonomous Agents and Multiagent Systems*, 1, pp. 543-551.

Zhang, Z., Liu, C., Chen, X., Zhang, C., Chen, J., 2017. Annual energy consumption of electric vehicle air conditioning in China. *Applied Thermal Engineering*, 125, pp. 567-574.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Equivalent Contact Temperature (ECT) for personal comfort assessment as extension for ISO 14505-2

Carolin Schmidt[1], Daniel Wölki[1], Henning Metzmacher[1] and Christoph van Treeck[1]

[1] Institute of Energy Efficiency and Sustainable Building (E3D), RWTH Aachen University, Germany, schmidt@e3d.rwth-aachen.de

Abstract: This paper introduces a new calculation method for the determination of the so-called equivalent contact temperature (ECT). It completes the missing contact area related thermal comfort information that is currently neglected in (ISO 14505-2, 2016), but which is inevitable for the evaluation of the local and overall thermal comfort of passengers in vehicles. There is strong evidence that currently used central HVAC units, which are based on convective heating and cooling of entire vehicle cabins will be replaced by various combinations of much more energy efficient decentralized systems that locally act on the human body in the future. However, such concepts must be able to provide the same level of thermal comfort to the passengers as currently existing HVAC systems to guarantee their acceptance. For this reason, the work at hand introduces an appropriate evaluation scheme, which holds for summer and winter test settings. Introduced experimental results provide the fundamental correlations between ECTs and corresponding thermal comfort votes for two distinct summer settings. The latter are made compatible to the existing evaluation schemes of (ISO 14505-2, 2016).

Keywords: contact area, decentralized climatization, equivalent temperature, energy efficiency, ISO 14505-2

1. Introduction

The ISO 14505 standard is intensively applied for thermal comfort assessment within the vehicle sector.

It is based on the determination of equivalent temperatures (T_{eq}) that consider the dry heat transfer (longwave radiation, convection) between the surface areas of exposed body locations and their surrounding microclimates. In this connection, T_{eq} can be applied to confined spaces with highly asymmetric radiant/flow fields, which predestines the index for the evaluation of human thermal comfort in vehicles. However, body locations that are in contact with their surrounding surfaces (palms, buttock, upper and lower back) cannot be evaluated. At such locations, it has to be distinguished between sensible (conduction) and latent (evaporation of sweat) heat transfer, which were not considered in the original definition of T_{eq} (Nilsson, 2004). Nevertheless, it is common practice to evaluate the overall thermal comfort of passengers in vehicles as the average value of the thermal comfort votes of local body locations (except of the contact areas). Taking into consideration that contact areas represent about 25 % of the heat exchanging surface area of the human body (Schmidt, 2016) would therefore end up in a prediction error of a comparable order. This is of special importance in connection with ongoing developments in the vehicle industry, where conventional combustion engines will be successively replaced by electric or hybrid drives. Here, conventional centralized HVAC systems that are heating and cooling the entire air volume of a vehicle cabin can no longer be used, because the required energy for the climatization of passengers must be entirely provided by the vehicle's battery, which is directly linked to its driving range.

Today, there is strong evidence that the vehicle sector actively works on the development of decentralized HVAC systems that will be based on a combination of various decentralized systems that operate on the level of individual body parts. Consequently, this increases the exergetic level of the entire system, which makes it more energy efficient. However, the evaluation of such systems in the context of human thermal comfort requires adequate thermal comfort assessment methods that have to be part of the control strategy. Here, the equivalent temperature approach described in (ISO 14505-2, 2016) can serve as a starting point for such thermal comfort based climatization strategies, presuming the contact areas are included in the existing evaluation schemes.

This paper introduces the mathematical formulation of the so-called equivalent contact temperature (ECT), which holds for summer and winter test settings. It contains the formal definition of ECT and provides the fundamental correlations between the ECTs at the contact interface between the passenger and the seat surface as well as the corresponding local subjective comfort votes for two different summer test settings. It further describes the resulting thermal comfort evaluation scheme, which was made compatible to the existing evaluation scheme of (ISO 14505-2, 2016).

2. Formal definition of the equivalent contact temperature (ECT)

The following formal definition for the introduced equivalent contact temperature (ECT) is suggested:

“The uniform temperature of an imaginary contact surface, at room air speed close to zero, at which a person will exchange the same amount of dry heat through thermal conduction as in the actual non-uniform environment, where the person experiences sensible and latent heat transfer at the considered body parts.”

The correlation between the highly non-uniform real situation at the interface between the seat surface and the human body as well as its uniform equivalent is depicted in Figure 1. The depicted terms of the shown mathematical equation are described in more detail in section 4.

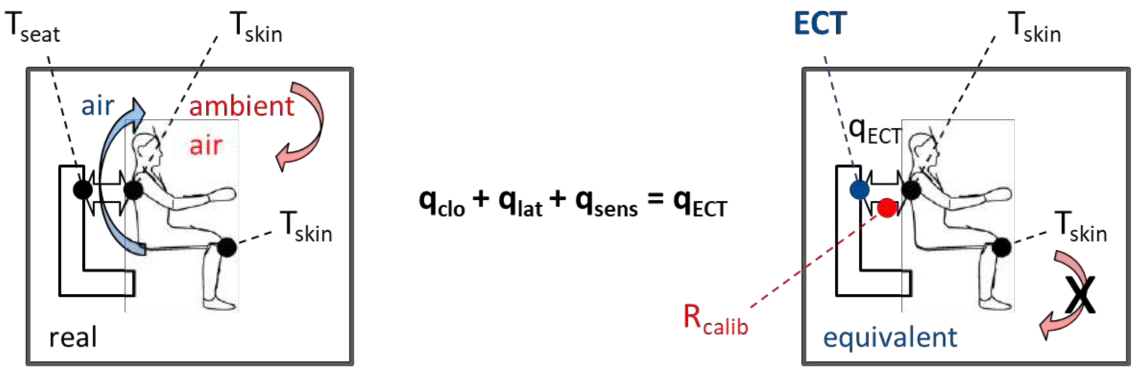


Figure 1. Definition and physical interpretation of the equivalent contact temperature (ECT); left-hand side: non-uniform situation, right-hand side: uniform equivalent; T_{seat}: seat surface temperature [°C], T_{skin}: local skin temperature [°C], v_{air}: air speed at the contact interface [m/s], ECT: equivalent contact temperature [°C], q_{clo}: heat flux density through clothing [W/m²], q_{lat}: latent heat flux density caused by evaporation of sweat [W/m²], q_{sens}: sensible heat flux density at the contact interface [W/m²], q_{ECT}: equivalent heat flux density [W/m²].

3. Methodology

As shown in section 2, ECT considers dry, latent and sensible heat transfer mechanisms at the contact interface between a person and the contacting surface, which might as well be a ventilated seat.

The left-hand side of Figure 2. schematically depicts the corresponding mechanisms by the use of a generalized h-x diagram that contains lines of constant temperature (T_1, T_2), lines of constant humidity (φ), lines of constant enthalpy (h), absolute humidity (x_1, x_2, $x_{2'}$) and the difference in specific humidity (Δx) between different states, marked with the numbers 1, 2, 2’ and 3. The following section explains the general idea behind ECT for the summer case, where a cooling of local body parts is of high interest.

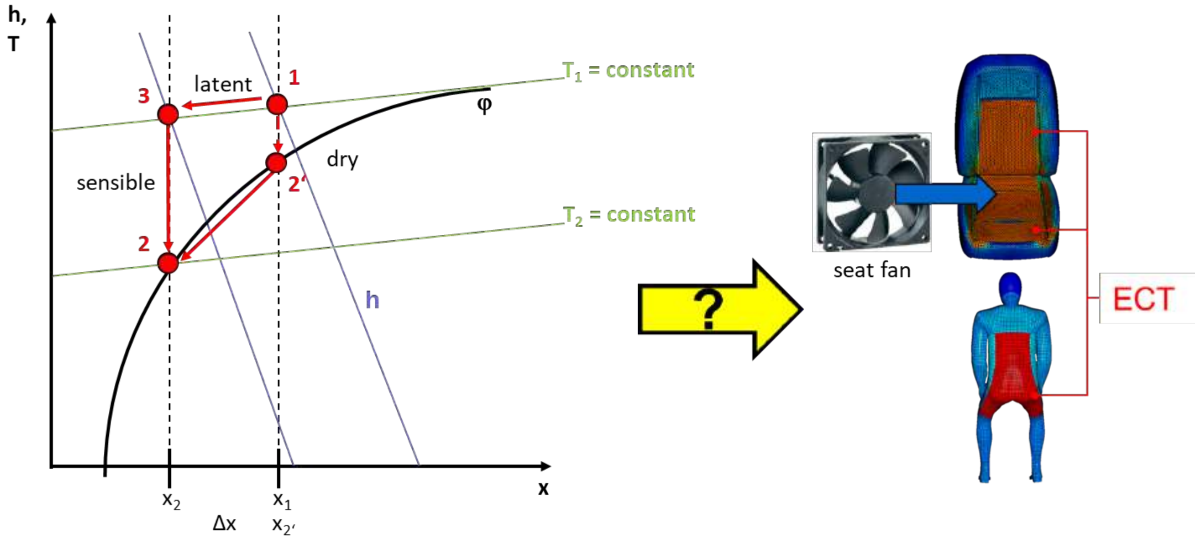


Figure 2. General idea for the calculation of ECT; left-hand side: generalized Mollier diagram, right-hand side: cooling of the contact area between the human body and the seat surface for a ventilated seat; T_1, T_2: isotherms, φ: relative humidity, h: lines of constant enthalpy, x_1, x_2, $x_{2'}$: specific humidity, Δx: difference in specific humidity between the different states 1, 2, 2’, 3

The goal is to reach state 2 in the h-x diagram of Figure 2. starting at state 1. In reality, this state can be reached by cooling down the air volume (without condensation), which would cause a vertical change from state 1 to state 2’. A subsequent dehumidification of the air volume (with condensation) would finally end up at the desired state 2. However, this is linked to an additional temperature change.

Mathematically, however, state 2 can be also reached by splitting the entire process in a sensible (state 1 to state 3) and latent (state 3 to state 2) component. This approach represents the theoretical base for the later described calculation approach of ECT. The corresponding mathematical framework is described in detail in section 4.

4. Fundamental equations

As stated before, (ISO 14505-2, 2016) contains no evaluation criteria for thermal comfort at the contact interface between a person and the vehicle interior.

Possible contact areas are steering wheel, seat surface, headrest, centre console as well as the side linings. However, the work at hand focusses on the contact interfaces between the human being and the seat surface. The corresponding mathematical model was derived from experiments with heated and ventilated seats, thus it is applicable for summer and winter settings.

4.1. Equivalent contact temperature (ECT)

The calculation of ECT puts special emphasis on the thermodynamic situation at the interface between the human skin and the seat surface.

Here, local heat transfer is considered as the combined effect of conduction and the change in enthalpy due to sensible and latent heat transfer caused by a local air flow between the skin/seat surface. As mentioned earlier, the introduced methodology follows the principle of T_{eq}. Consequently, it requires the equality between the heat flux density at the contact interface q_{ECT} [W/m²] in a uniform environment and the sum of the heat conducted through local clothing layers (q_{clo}), latent heat flux density q_{lat} [W/m²] and sensible heat flux density q_{sens} [W/m²] in the real non-uniform situation (1).

$$q_{ECT} = q_{clo} + q_{lat} + q_{sens} \tag{1}$$

Here, q_{clo} is calculated according to equation (2), where T_{skin} [°C] represents the skin temperature of a person at the contact interface, T_{seat} [°C] the corresponding seat surface temperature and R_{clo} [m²·K/W] the clothing resistance factor of a clothing combination worn by person. The latter can be calculated from the more commonly known clothing insulation I_{cl} [clo], where 1 clo = 0.155 m²·K/W (ISO 9920, 2007).

$$q_{clo} = \frac{1}{R_{clo}} \cdot (T_{skin} - T_{seat}) \tag{2}$$

The latent heat flux density q_{lat} is calculated as the mass flow rate $\dot{m}_{air}$ [kg/s] that is generated by the seat fans, r_0 [kJ/kg] the specific heat for the vaporization of water (= 2256 kJ/kg), c_{PD} [J/kg·K] the specific heat capacity of water vapour (= 2080 J/kg K), x_{seat} [kg/kg] the specific humidity at the contact surface, x_{air} [kg/kg] the specific humidity of the surrounding air and $A_{contact}$ [m²] the surface area of the contact interface between the human body and the human being. In the work at hand, $A_{contact}$ was extracted from numerical human model, which represents an average human being with respect to its anthropometrical constraints (Wölki, 2017).

$$q_{lat} = \frac{\dot{m}_{air} \cdot (r_0 + c_{PD} \cdot T_{seat}) \cdot (x_{seat} - x_{air})}{A_{contact}} \tag{3}$$

The sensible heat flux density q_{sens} of equation (1) is calculated by equation (4), where c_{PL} [J/kg·K] is the specific heat of dry air (= 1005 J/kg·K) and T_{air} [°C] the ambient temperature.

$$q_{sens} = \frac{\dot{m}_{air} \cdot (c_{PL} + x_{air} \cdot c_{PD}) \cdot (T_{seat} - T_{air})}{A_{contact}} \tag{4}$$

The unified equivalent heat flux density q_{ECT} is determined and defined by equation (5). Here, the parameter R_{calib} [m²·K/W] represents the thermal resistance factor between ECT and the skin temperature T_{skin}. In this work R_{calib} was set to 0.03875 m²·K/W, which represents the average value of a vehicle seat with an I_{cl} value of 0.25 clo according to (ISO 9920, 2007).

$$q_{ECT} = \frac{1}{R_{calib}} \cdot (T_{skin} - ECT) \tag{5}$$

Replacing q_{ECT} on the right-hand side of equation (1) by equation (5) as well as the single terms on the right-hand side of equation (1) by equations (2) to (4) leads to equation (6) and finally enables the calculation of ECT.

$$ECT = T_{skin} - \left[\frac{R_{calib}}{R_{clo}} \cdot (T_{skin} - T_{seat}) + \frac{R_{calib} \cdot [\dot{m}_{air} \cdot (r_0 + c_{PD} \cdot T_{seat}) \cdot (x_{seat} - x_{air})]}{A_{contact}} + \frac{R_{calib} \cdot [\dot{m}_{air} \cdot (c_{PL} + x_{air} \cdot c_{PD}) \cdot (T_{seat} - T_{air})]}{A_{contact}}\right] \quad (6)$$

5. Thermal comfort evaluation

Figure 3 shows two standardized evaluation schemes for the assessment of body part specific thermal comfort for a typical summer (centre) and a typical winter case (right-hand side) according to ISO 14505-2.

The corresponding schemes were introduced by (Nilsson, 2004), who linked local equivalent temperatures, measured with a thermal manikin, to subjective thermal sensation and comfort votes of persons. To enable this, each subject of this study was exposed to the same experimental conditions as the appropriate thermal manikin. Later on, his work became part of the international standard (ISO 14505-2, 2016), in which the charts below are included.

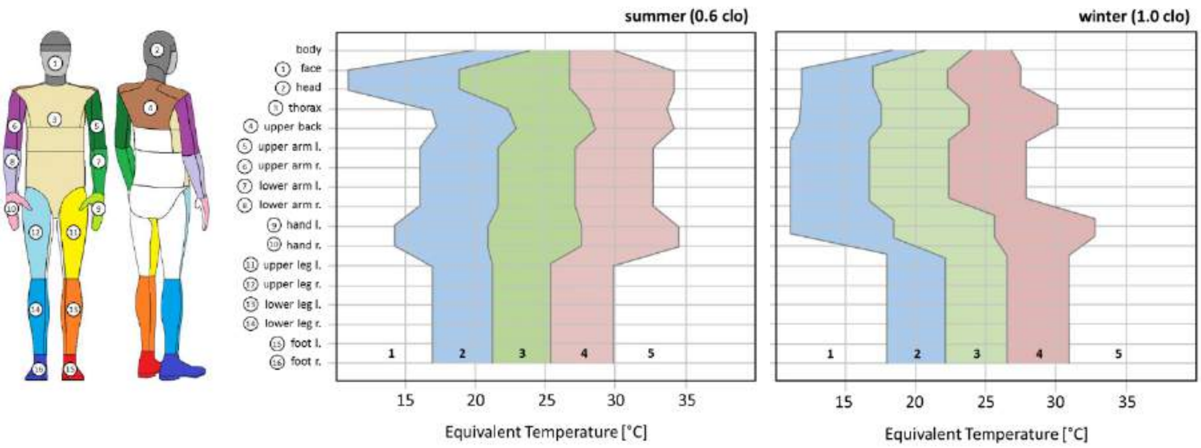


Figure 3: Evaluation schemes for body part specific equivalent temperatures (ISO 14505-2, 2016); left-hand side: schematic of the body segments that can be assessed with T_{eq}, centre: thermal comfort evaluation scheme for summer conditions (applicable for a clothing insulation of 0.6 clo), right-hand side: thermal comfort evaluation scheme for winter conditions (applicable for a clothing insulation of 1.0 clo).

The above shown diagrams consist of two axes, where each y-axis depicts 16 body parts as well as the entire human body. The corresponding x-axes hold the appropriate equivalent temperatures of each body part, which range from 10 °C to 40 °C. The coloured zones in the diagrams represent the evaluated equivalent temperatures by the use of the so-called mean thermal vote (MTV). The latter were derived on the basis of a five-point Bedford scale, which mixes thermal comfort and thermal sensation (1 = too cold, 2 = cold but comfortable, 3 = neutral, 4 = warm but comfortable, 5 = too warm). The illustration of the human body on the left-hand side of Figure 3 clearly shows that the dorsum and clunis (white coloured areas) are currently neglected in the evaluation scheme and cannot be assessed so far.

However, for the evaluation of the efficiency of decentralized climatization systems that locally act on those body locations, the extension of the schemes is obligatory.

6. Experiments

The experiments described in this paper were conducted during the late summer from September till the middle of October at E3D, RWTH Aachen University.

In total 35 subjects (18 females and 17 males) were investigated. In this work, the results of 14 subjects are shown. The corresponding experimental set-up, measurement equipment as well as the experimental design is detailed in the subsequent sections.

6.1. Measurement equipment and experimental set-up

The calculation of ECT according to equation (6) required extensive sensor hardware for the seat.

A schematic of the corresponding sensors as well as of their location on the seat is illustrated in Figure 4. Here, the mass flow rate measurement devices (MFRMDs) are devices that have been developed and work on a calorimetric principle. They were connected to an Arduino Due (Arduino) microcontroller board, used to control the corresponding power electronics of the sensors. The pressure, humidity and temperature sensors BME 280 (Bosch, Germany), were attached to the seat to measure the relative humidity and temperature at the clothing surface of the subject. Additional Kritec PT100 sensors were used to obtain the temperature information of the seat surface.

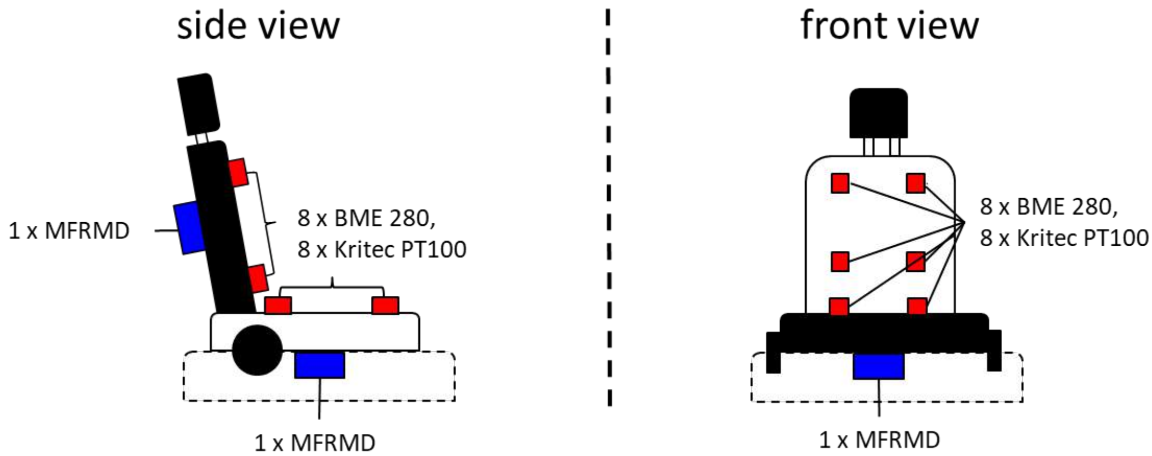


Figure 4: Schematic of the a seat, equipped with the corresponding measurement devices; BME 280: humidity and temperature sensor, Kritec PT100: temperature sensor, MFRMD: in-house developed sensor for the measurement of the mass flow rate delivered by the fans, mounted at the backside of the backrest and the backside of the cushion

The human skin temperature as well as the corresponding relative humidity at the skin surface was measured with iButtons of type DS 1923-F5 (Maxim Integrated). Each subject was equipped with 8 sensors that were mounted at the back and dorsum of the person. The corresponding sensor locations were chosen to be close to BME 280 sensors as soon as the person was sitting on the seat.

To be able to assess the ambient conditions within the test facility, a comfort measurement device of the German company Ahlborn was used. The latter consisted of a data logger (2690 8A), a globe thermometer (ZA 9030-FS2), a humidity-/temperature sensor (FH A646-E1) and a thermo-anemometer (FVA605-TA1O). To manage the various data streams from the diverse sensor hardware, a data acquisition software was developed in the programming language Python.

6.2. Experimental design

The experimental design of this study is illustrated in Figure 5.

It shows a test cycle of a single person for two different temperature scenarios, which were defined to be 26 °C and 28°C. The latter was assumed to be high enough to cause warm discomfort and enabled the investigation of ventilation effects on a person's thermal comfort. During the experiment three persons were tested in parallel. They were assigned a predefined seat, which they could not switch during the entire experiment. Each day was divided into two stages. The first cycle started at 8.00 am and finished at 11.00 am, the second one started at 1.00 pm and finished at 4.00 pm. During the tests the persons wore clothing combinations with an overall insulation value of 0.5 clo. They were not allowed to change their clothing during the test.

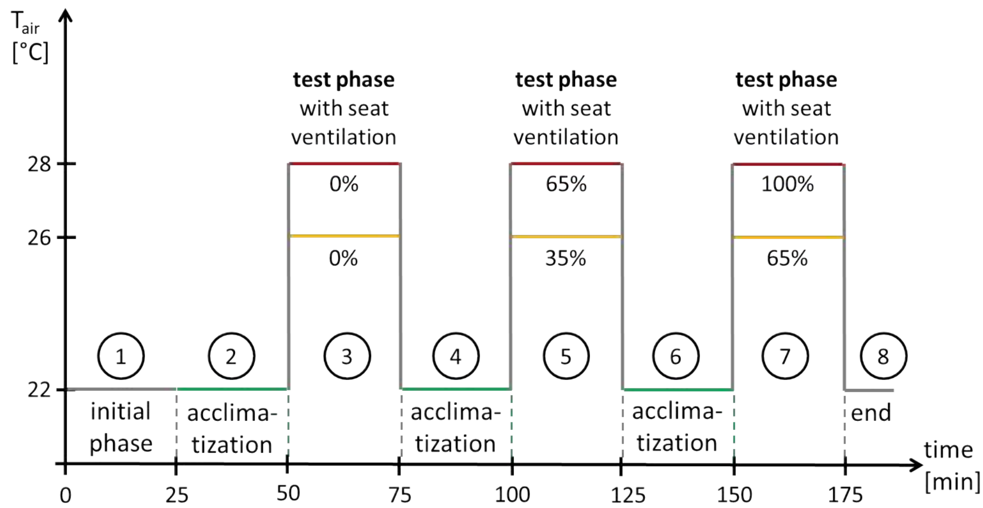


Figure 5: Example of test cycle for a single subject; schematic shows the two tested summer scenarios at temperatures of 26°C and 28°C; percentages indicate the relative fan speed, where 0 % means fan is switched off and 100 % represents the highest possible fan speed

In total, a single test cycle consisted of seven phases. The first phase is called the initial phase. During this phase, the subjects arrived at the test facility and were given the chance to calm down and focus on the experiment. It was followed by a 25 min acclimatization phase in which they were prepared for the experiment and during which they had to answer a first questionnaire that contained questions concerning their health state and their local and overall thermal comfort. Phases two to seven were alternated between a 25 min test phase and a subsequent acclimatization phase of the same length (22 °C). The latter was included to have a clear initial baseline for the human thermoregulatory system for each test phase. The percentages in each phase represent the different stages of the seat fans, where 0 % means the fans are switched off and 100 % that the fan is at its maximum level. The sequence of the corresponding ventilation stages, however, was chosen randomly to avoid possible learning effects.

The above mentioned questionnaire was designed on the base of (ISO 14505-2, 2016), using the five point Bedford scale. It contained questions on the local and overall thermal sensation and comfort as well as on the humidity sensation and satisfaction of a person. The latter was chosen in order to investigate, if human beings are really able to sense humidity.

However, the results are not part of this paper and will be subject to another publication. The thermal comfort survey itself was conducted during the initial 5 min and after 25 min of each test phase to be able to capture transient effects as well.

7. Results

The subsequent sections illustrate the results of the above described experiment.

In this regard, the depicted results represent average values of the 14 subjects that took part in the experiments described in section 6.

7.1. ECT and absolute humidity at contact areas

The first two diagrams show the transient behaviour of the calculated ECTs for both dorsum (Figure 6) and clunis (Figure 7).

In this regard, each figure depicts the corresponding values for a total of six test scenarios, where S26 - 0 to S26 - 2 represent the three test conditions for 26 °C ambient temperature at a seat fan level of 0 % (0), 35 % (1) and 65 % (2). Scenarios S28 - 0 to S28 - 3 the corresponding test conditions at 28 °C ambient temperature and seat fan levels of 0 % (0), 65 % (2) and 100 % (3), respectively.

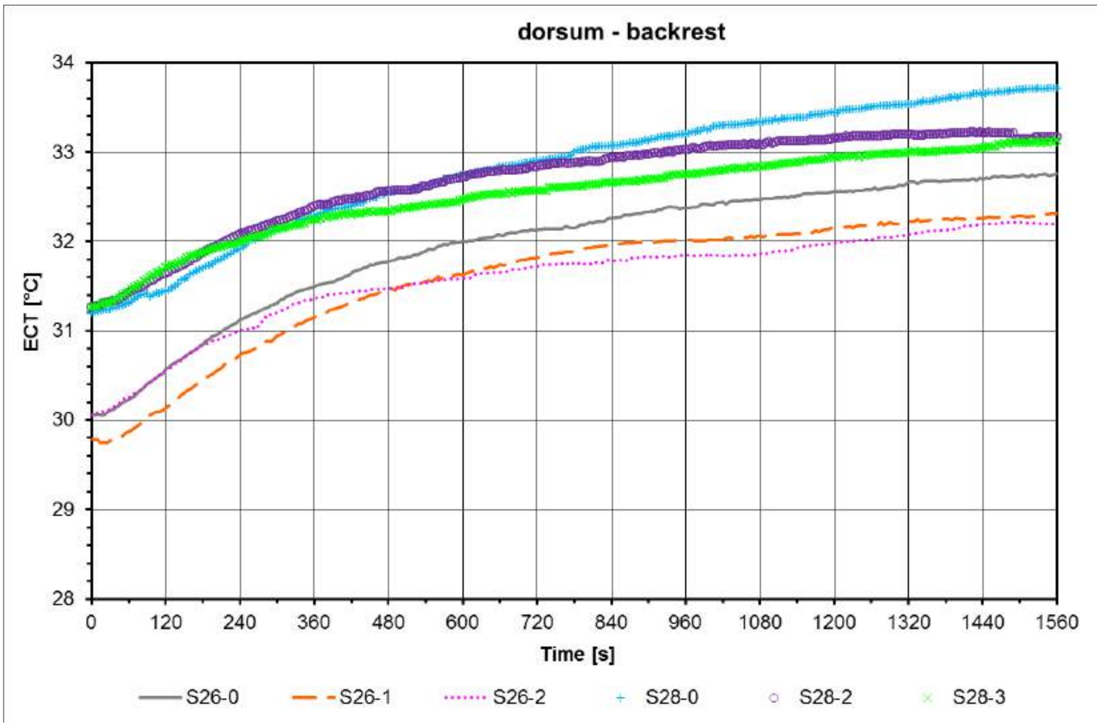


Figure 6: Transient behaviour of the calculated ECTs for the contact interface between the dorsum and the backrest of the seat; S26-0 to S26-2: test scenarios for 26 °C and fan levels of 0 %, 35 % and 65 %, S28-0 to S28-2: test scenarios for 28 °C and fan levels of 0 %, 65 % and 100 %

A constant increase in ECTs for all scenarios can be obtained during the corresponding 25 min test phases (Figure 6). Furthermore, all the different graphs show a linear increase during the initial 7 min of the experiment. Except for scenario S28 - 0, for which the seat fan was completely deactivated, all the signals reach a steady state at the end of the test phase. It can be seen that the two different test conditions can be clearly separated. In this regard, the ECTs calculated for scenarios S26 - 0 to S26 - 2 are constantly below the values of scenarios S28 - 0 to S28 - 3.

In addition, the influence of the different seat fan levels on the corresponding ECTs and the appropriate heat transfer at the contact interface between the dorsum and the backrest becomes apparent. It is expressed in the diverging curves of Figure 6, where the highest seat fan level causes the lowest ECT in each test phase and each temperature scenario. The same behaviour can be obtained for the contact interface between the clunis and the cushion of the seat (Figure 7).

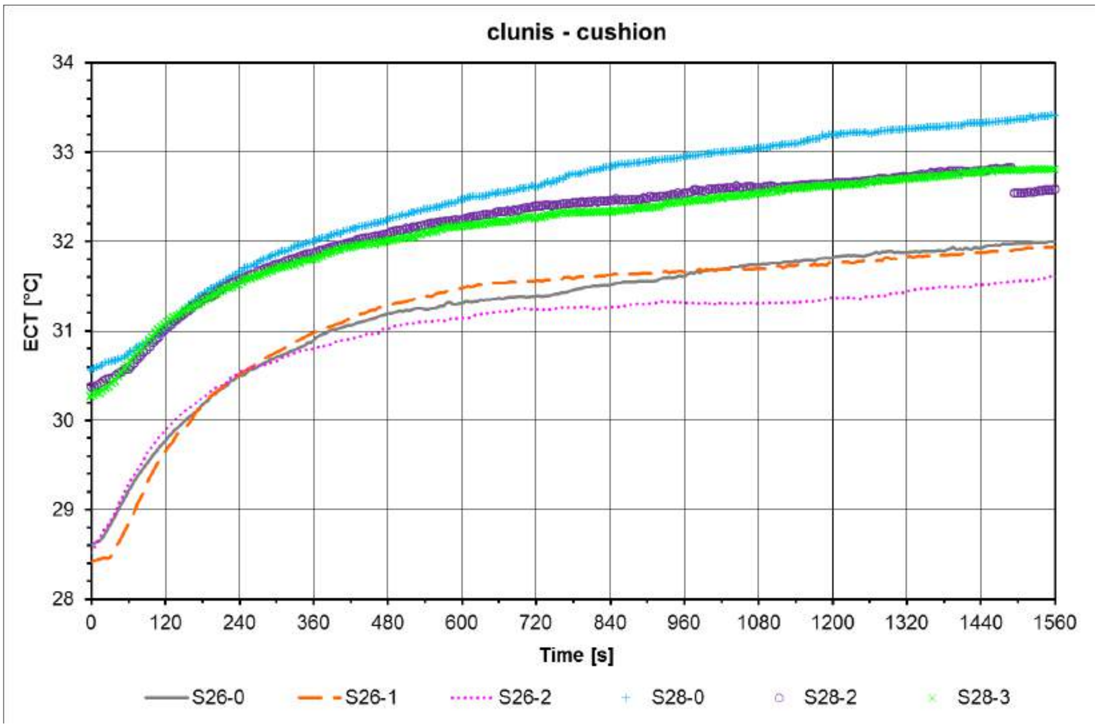


Figure 7: Transient behaviour of the calculated ECTs for the contact interface between the clunis and cushion of the seat; S26-0 to S26-2: test scenarios for 26 °C and fan levels of 0 %, 35 % and 65 %, S28-0 to S28-2: test scenarios for 28 °C and fan levels of 0 %, 65 % and 100 %

The transient behaviour of the absolute humidity at the skin surface and the air layer between the dorsum and the backrest of the seat for the 26 °C scenario is shown in Figure 8. It can be seen that the humidity values of the skin surface are constantly higher than the humidity values of the air layer at the backrest. In addition, the humidity values of the skin increase with decreasing fan levels. In this regard, the maximum absolute humidity was measured at the skin surface for a fan level of zero.

It is interesting to see that the humidity values of the skin and the air layer at the contact interface of the backrest show inverse behaviour. This demonstrates the influence of the seat fan level and the clothing insulation on the transport of sweat liquid through the different clothing layers of the subjects to the surface of the backrest. Furthermore, increasing fan levels cause a decrease of absolute humidity for both skin and air layer at the contact interface of the backrest.

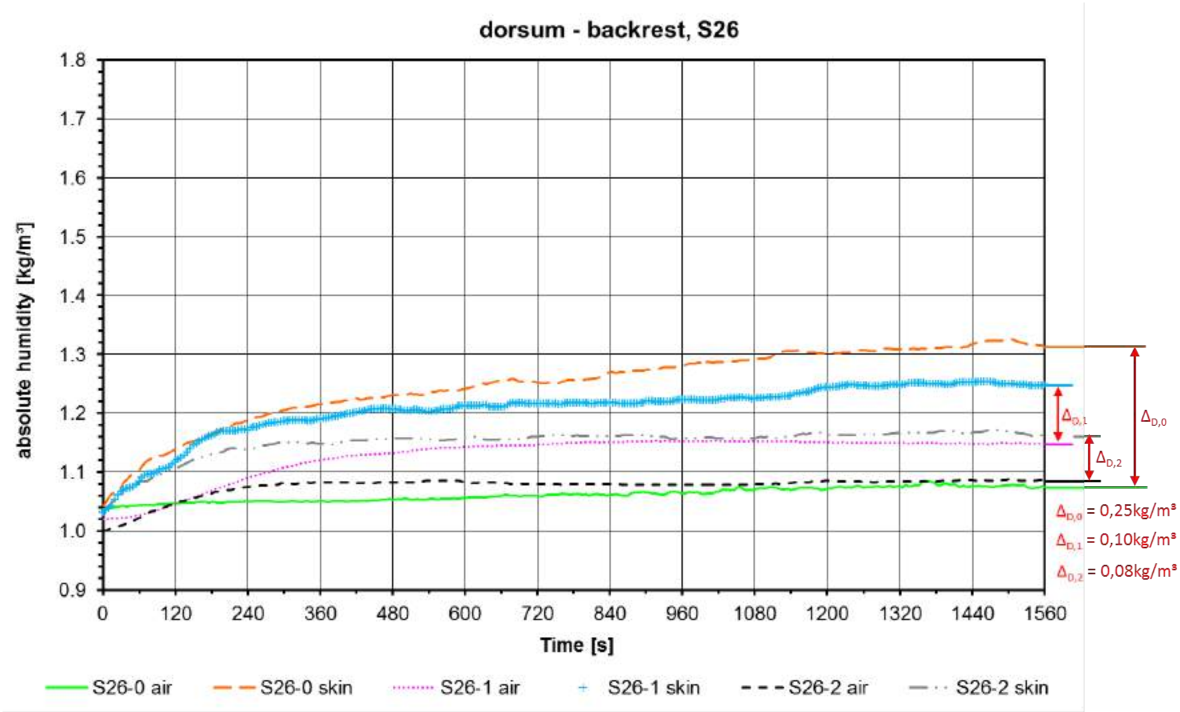


Figure 8: Transient behaviour of the absolute humidity at the contact interface between the dorsum and the backrest of the seat; S26-0 to S26-2: test scenarios for 26 °C and fan levels of 0 %, 35 % and 65 %

Figure 9 illustrates the absolute humidity values for the skin and the air layer at the contact interface between the clunis and the cushion of the seat and the 26 °C scenario. It becomes obvious that the absolute humidity values at skin surface of the clunis exceed the values measured at skin surface of the dorsum (Figure 8).

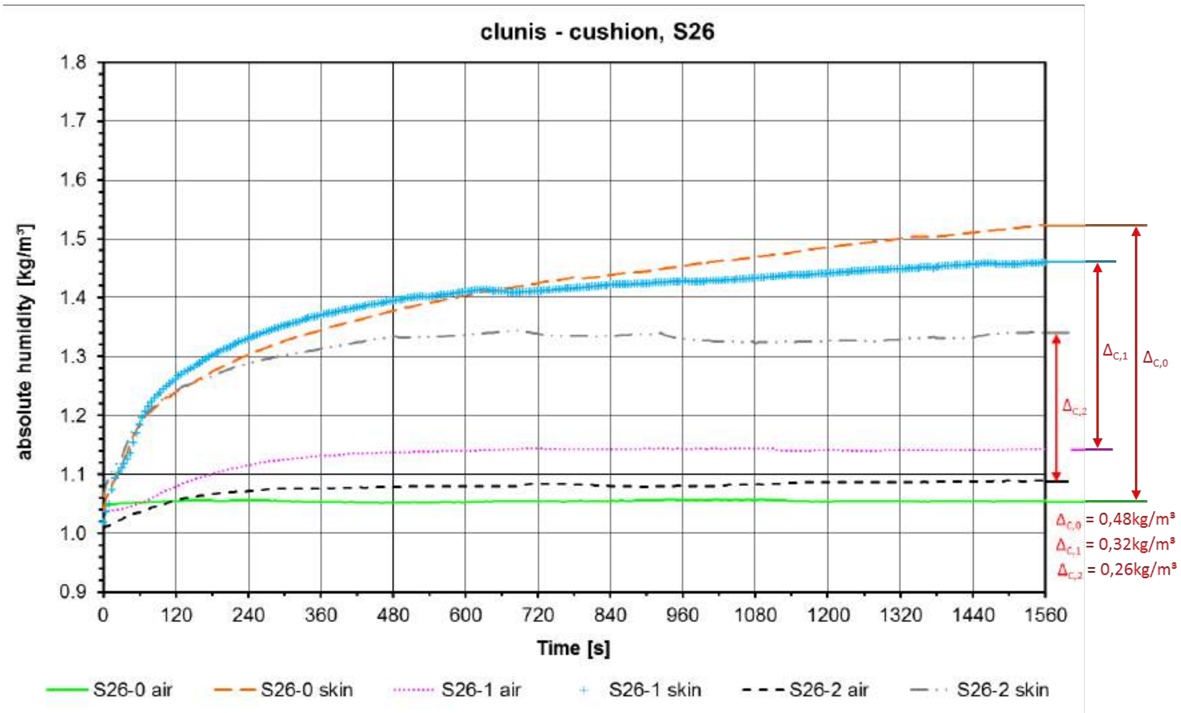


Figure 9: Transient behaviour of the absolute humidity at the contact interface between the clunis and the cushion of the seat; S26-0 to S26-2: test scenarios for 26 °C and fan levels of 0 %, 35 % and 65 %

As for the dorsum, the maximum absolute humidity is measured at the skin surface for a fan level of zero. Furthermore, it can be seen that the absolute humidity values of the air layer at the contact interface of the cushion are similar to the corresponding values of the backrest (Figure 8). In addition, a higher minimum absolute humidity for the skin surface is present, when compared to the corresponding value of the backrest. It once more highlights the influence of clothing insulation and fan level on the transport of sweat liquid through the clothing layers of the subjects.

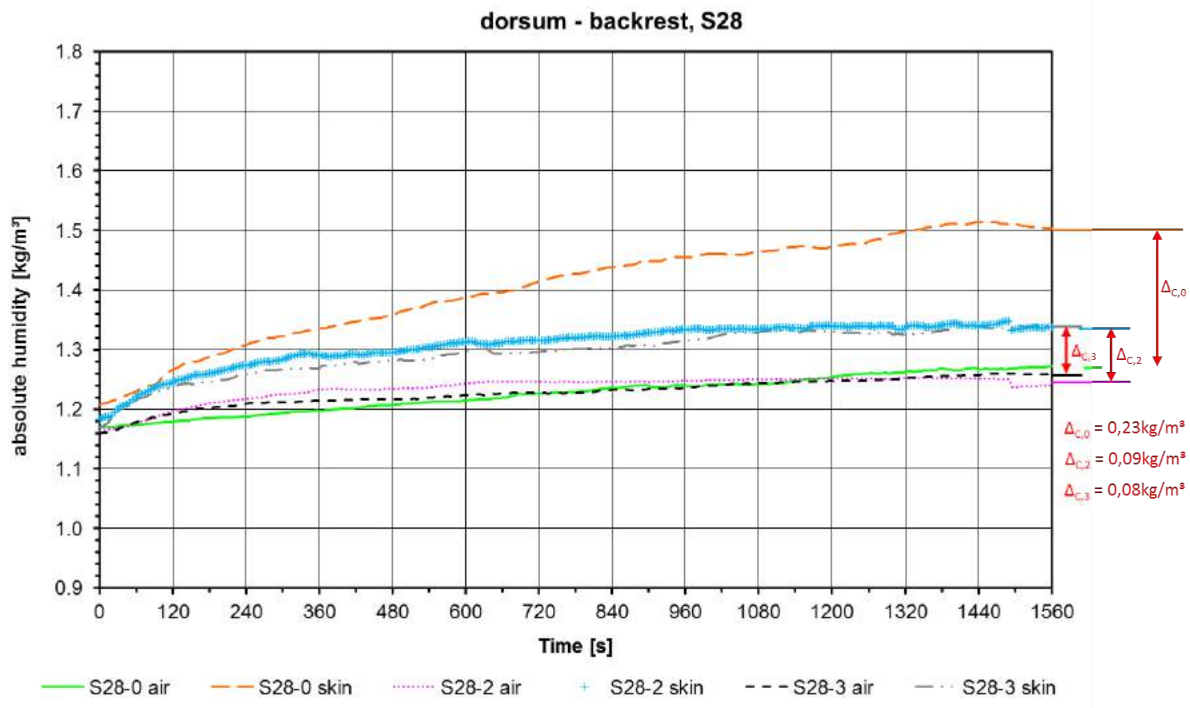


Figure 10: Transient behaviour of the absolute humidity at the contact interface between the dorsum and the backrest of the seat; S28-0 to S28-3: test scenarios for 28 °C and fan levels of 0 %, 65 % and 100 %

The absolute humidity measured at the dorsum and the backrest for the 28 °C scenario are depicted in Figure 10. As expected from the results of the 26 °C scenario, the difference in absolute humidity values for both skin and air layer at the backrest is smaller than for the dorsum and the cushion (Figure 11). In addition, the initial values for this contact interface are higher than for the corresponding contact area in the 26 °C scenario. This, however, indicates that the subjects showed an elevated sweat liquid production due to the higher ambient temperature of 28 °C. Nevertheless, the same correlation between the seat fan level, absolute humidity and clothing insulation can be observed as for the 26 °C scenario.

Corresponding results for the contact interface between the clunis and the seat cushion are shown in Figure 11. Again, the highest absolute humidity can be obtained for the skin surface of the clunis. Furthermore, the initial values for the skin surface and the air layer at the contact interface of the cushion are higher than their counterparts of the 26 °C scenario. As for the above mentioned results for the contact interface of the backrest, the higher initial values indicate an elevated sweat liquid production that can be attributed to the higher ambient temperatures. The inverse behaviour of the absolute humidity for the skin surface and the air layer at the contact interface of the seat cushion is present as well. It confirms the corresponding prior observations for the 26 °C scenario.

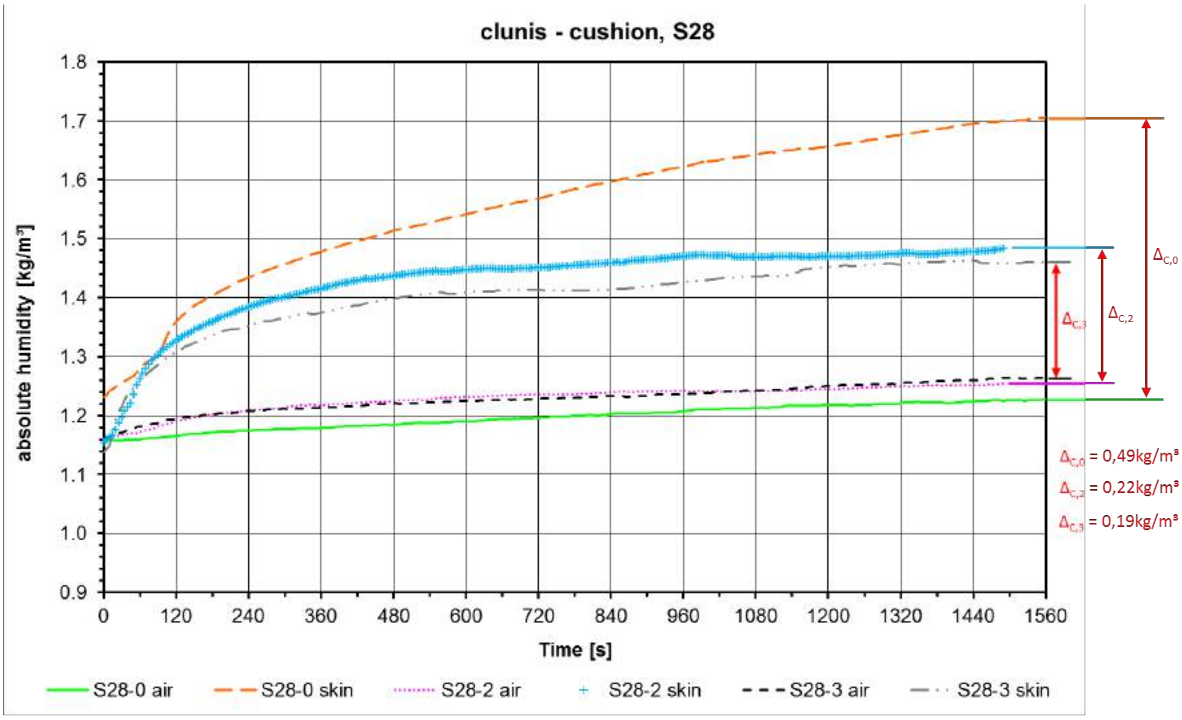


Figure 11: Transient behaviour of the absolute humidity at the contact interface between the clunis and the cushion of the seat; S28-0 to S28-3: test scenarios for 28 °C and fan levels of 0 %, 65 % and 100 %

7.2. MTVs for the contact areas

This subsection describes the resulting MTVs for the clunis (left-hand side, Figure 12) and the dorsum (right-hand side, Figure 12) that were derived on the base of the questionnaires mentioned in subsection 6.2 and temperature scenarios of 26 °C and 28 °C.

The corresponding boxplots for the clunis show a left skewed data distribution for scenario S26 - 0, which strongly tends towards the "too warm" vote of +5.

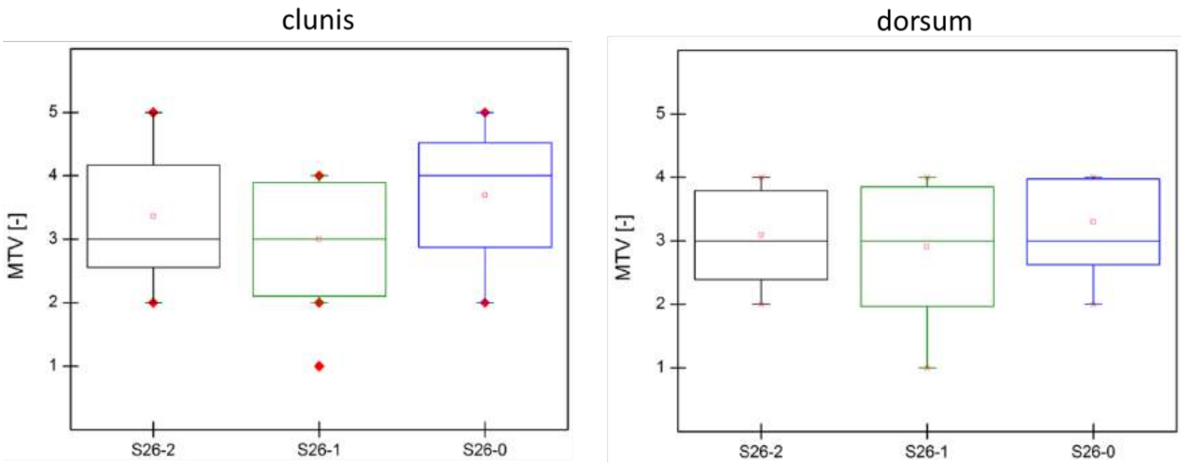


Figure 12: Results of the MTVs at the clunis (left-hand side) and the dorsum (right-hand side); S26-0 to S26-2: test scenarios for 26 °C and fan levels of 0 %, 35 % and 65 %; small boxes in the middle of the boxplot: mean value, whiskers: minimum and maximum values of the data set, solid line in the middle of the boxplot: median, data points outside the whiskers: outlier

The appropriate temperature scenario S26 - 1 depicts a normally distributed data set with a median value of +3 ("neutral"). The illustrated extreme value can be neglected, because it does not fit to the symmetric distribution of the dataset. Consequently, it can be regarded as an outlier. Temperature scenario S26 - 2, is right skewed and shows a median of +3 (“neutral”).

The results of the dorsum on the right-hand side of Figure 12 for scenario S26 - 0 strongly tend towards the “neutral” vote of +3. For scenario S26 - 1 a left skewed data distribution is present. The corresponding median is equal to +3 (“neutral”) as well, however the dataset is mainly concentrated above the median, indicating a strong tendency towards the “warm but comfortable” vote (+4). Furthermore, the variability of the dataset is the highest of all the datasets. The right skewed data distribution of S26 - 2 indicates a strong tendency towards a “cold but comfortable” vote with a median value of +3 (“neutral”).

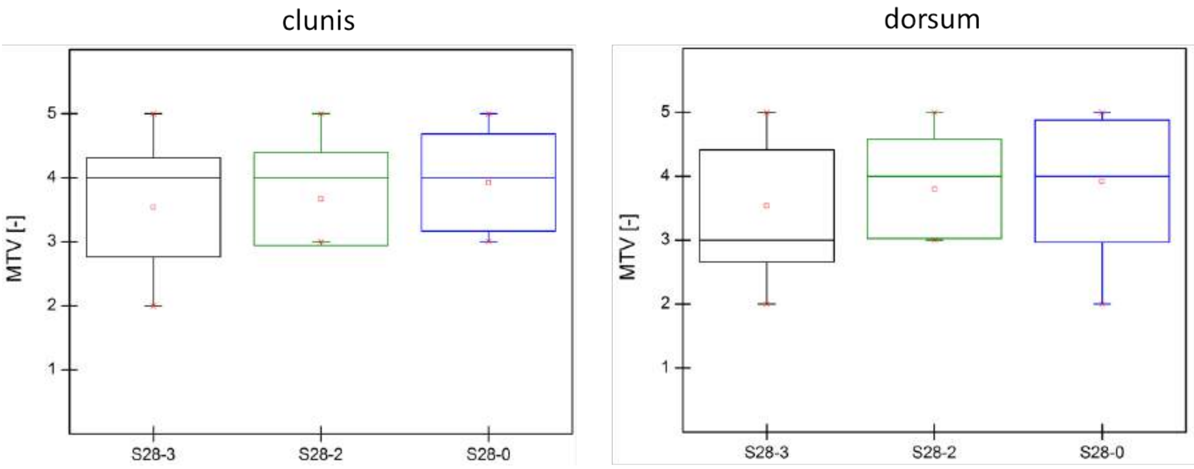


Figure 13: Results of the MTVs at the clunis (left-hand side) and the dorsum (right-hand side); S28-0 to S28-3: test scenarios for 28 °C and fan levels of 0 %, 65 % and 100 %; small boxes in the middle of the boxplot: mean value, whiskers: minimum and maximum values of the data set, solid line in the middle of the boxplot: median, data points outside the whiskers: outlier

Corresponding MTVs for clunis and dorsum of the temperature scenarios S28 - 0 to S28 – 3 are illustrated in Figure 13. In this connection, the MTVs for the clunis show a decreasing tendency in the central 50 % of the data with increasing fan levels. Here, scenario S28 - 0 shows a median value of +4 (“warm but comfortable”) with a slightly left skewed dataset, indicating a tendency towards the “too warm” vote of +5. For S28 - 2, a left skewed data distribution can be obtained with a median of +4 (“warm but comfortable”). The same can be obtained for the left skewed data distribution of scenario S28 - 3. However, in this scenario the variance in the central 50 % of the dataset is higher than in the remaining scenarios.

The right-hand side of Figure 13 illustrates the corresponding MTVs of the dorsum. As for the clunis, the boxplots show a decreasing tendency in the central 50 % of the datasets, which can be again linked to the increasing fan levels. In this regard, scenario S28 - 0 shows a left skewed data distribution with a median of +4 (“warm but comfortable”) and a strong tendency towards +5 (“too warm”). In S28 - 1 a left skewed distribution of the dataset and a median value of +4 (“warm but comfortable”) are present as well. However, S28 - 1 shows a smaller variance in the central 50 % of the dataset than the remaining scenarios. Finally, the dataset of scenario S28 - 3 is right skewed, with a median of +3 (“neutral”) and a strong tendency towards a “cool but comfortable” vote of +2.

7.3. Correlation between ECT and MTV

Figure 14 shows the correlation between the ETCs and MTVs for clunis and dorsum.

The diagram was inspired by (ISO 14505-2, 2016) and can be regarded as a first suggestion of a thermal comfort evaluation scheme for the contact interface between a seat and a person. The depicted scheme is regarded as valid for summer conditions and clothing insulations of 0.6 clo.

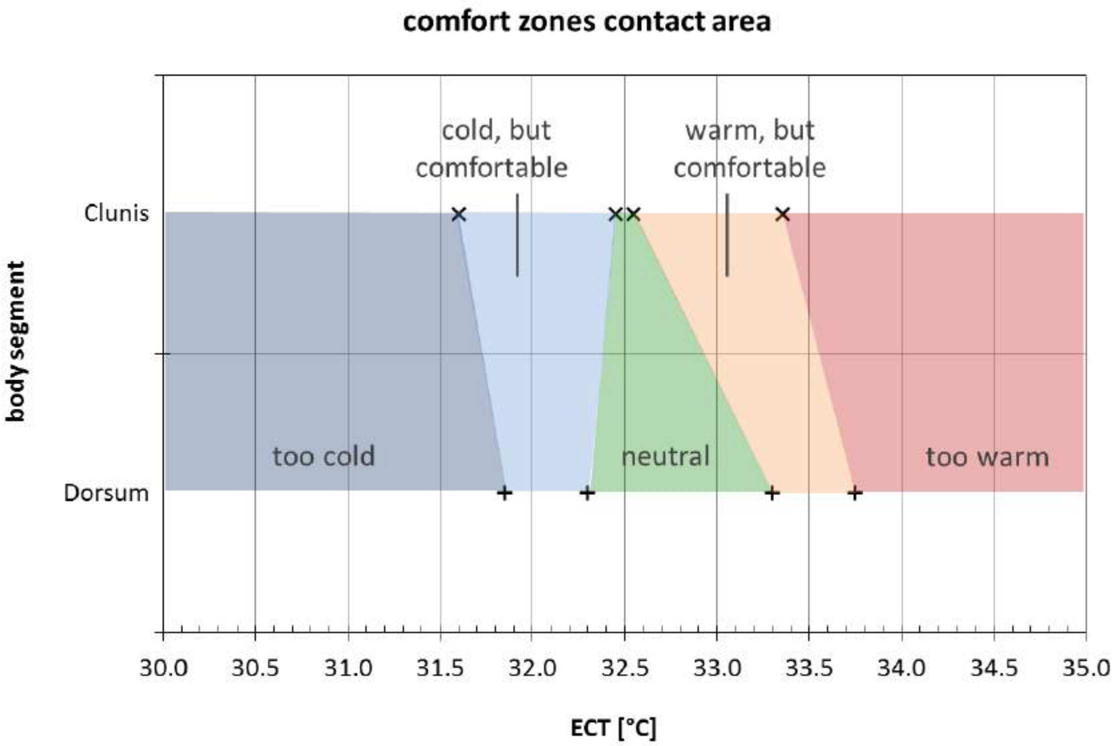


Figure 14: Thermal comfort evaluation scheme for the contact interface between clunis, dorsum and the seat surface. The scheme is suggested to be applicable for summer conditions and a clothing insulation values of 0.6 clo

To be compliant with (ISO 14505-2, 2016), the body parts of the contact area are plotted on the y-axis. The corresponding ETCs on the x-axis. In this regard, the outer boundaries of the ECT-interval were specified between 30.0 °C and 35 °C. However, those boundaries must be regarded as a first suggestion and might change with additional experimental input data. The crosses in Figure 14 represent the ECTs from the two ambient scenarios and the six seat fan levels that were calculated on the measurement results of the 14 subjects. In this regard, the ECTs were sorted with respect to the corresponding MTVs. In a next step, the maximum and minimum ETCs for each MTV-interval were extracted and averaged to be able to define the above shown boundaries for the five comfort intervals.

8. Discussion

The ECTs depicted in Figure 6 and Figure 7 clearly demonstrate the effects of the ambient temperature and the seat fan on the ECTs at the contact interface between the seat and human body.

In this regard, the backrest shows higher initial ECTs than the corresponding cushion for the 26°C and the 28 °C scenario. This can be attributed to the different orientations in space of both seat components (cushion, backrest) as well as to the construction of the seat itself. In addition, a steeper increase of the ECTs at the clunis can be observed for both ambient conditions. This is once more related to the lower initial ECTs at those regions.

Furthermore, the highest ECT signal is always measured for scenarios, in which the seat fan was completely deactivated. For those conditions, the highest absolute humidity values can be obtained for the skin surface of the person (Figure 8 to Figure 11). Simultaneously, the air layers at the contact interfaces of the seat show the lowest humidity values. This clearly demonstrates the necessity of involving adequate clothing characteristics in the calculation of the suggested ECTs.

In addition, the increasing seat fan levels cause decreasing absolute humidity values at the skin and increasing humidity values at the contact interfaces for all test conditions. This illustrates the influence of the seat fans on the humidity transport (sweat liquid) through the clothing layers. In this regard, the absolute humidity values at the cushion exceed the values at the backrest in all test conditions (Figure 8 to Figure 11). This can be attributed to the higher contact pressure caused by a person's body weight and is linked to the person's posture, too. The latter, is mainly influencing the results of the backrest, since in a general use case the position of the clunis is predominantly fix during the time the person is driving the vehicle, whereas the dorsum offers much more degrees of freedom with respect to its movement.

An additional aspect is that the absolute humidity values at the contact interfaces show higher absolute values for the 28 °C scenario for both, the skin surface and the air layer (Figure 8 to Figure 11). This, however, can be explained by the activity of the human thermoregulatory system that elicits an increased sweat production.

Furthermore, it can be seen that the steady state of the absolute humidity values can only be reached during the test phases of 25 min, in which the seat fans were activated. This highlights the dependency between absolute humidity, ECT, seat fan level and enthalpy (Figure 8 to Figure 11). In this connection, the air flows elicited by the seat fans cause an immediate removal of sweat liquid from the skin surface to the contact interface between the human body and the seat. The temperature drop caused by the evaporation of sweat in the mechanically removed air volume is reflected in the lower ECTs (Figure 6 and Figure 7), which finally confirms the applicability of the suggested mathematical framework for the calculation of ECT (section 3 and subsection 4.1).

Finally, the suggested comfort diagram depicted in Figure 14 can be used as first suggestion for the thermal comfort evaluation at the dorsum and the clunis. However, the sampling size of the statistical analysis has to be increased to be able to reliably define the boundaries for the corresponding MTVs. This, however, will be done in the next step.

9. Conclusion

This paper introduced a first suggestion for a formal definition and a mathematical framework for the calculation and evaluation of the local thermal comfort at the contact interfaces between a person and a seat.

The suggested approach was based on the so-called equivalent contact temperature (ECT), which describes the temperature of a homogenous room, in which a person experiences the same sensible and latent heat exchange through conduction and evaporation as in the actual non-uniform situation. The applicability of the calculation procedure was investigated with experiments. Corresponding results showed a good match with the general theory of thermodynamics. Thermal comfort at the contact interfaces was investigated on the base of mean thermal votes (MTVs) to be compliant with (ISO 14505-2, 2016). A first suggestion of an evaluation scheme that correlates ECTs and MTVs at the clunis and the dorsum of a person was derived. The corresponding comfort intervals must be regarded as a first suggestion and might shift with increasing sampling size. The necessary statistical analysis of the experiments is currently in progress.

10. References

ISO 9920, 2007. *Ergonomics of the thermal environment – Estimation of thermal insulation and water vapour resistance of a clothing ensemble*

ISO 14505-2, 2016. *Ergonomics of the thermal environment - Evaluation of thermal environments in vehicles - Part 2: Determination of equivalent temperature*

Nilsson, H. O., 2004. *Comfort Climate Evaluation with Thermal Manikin Methods and Computer Simulation Models*. PhD. University of Gävle

Schmidt, C., 2016. *Entwicklung eines Modellansatzes zur Bewertung der thermischen Behaglichkeit unter inhomogenen Klimabedingungen*. PhD thesis. RWTH Aachen University

Wölki, D., 2017. *MORPHEUS: Modelica-based implementation of a numerical human model involving individual human aspects*. PhD thesis. RWTH Aachen University

Acknowledgement

Experimental data originate from a project of the Research Association of Automotive Technology (FAT), which was financially supported by the German Association of the Automotive Industry (VDA).

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Thermal comfort-driven feedback control for electric vehicles based on thermal image recognition, passenger tracking and thermophysiological modelling

Daniel Wölki[1], Henning Metzmacher[1], Carolin Schmidt[1] and Christoph van Treeck[1]

[1] Institute of Energy Efficiency and Sustainable Building (E3D), RWTH Aachen University, Germany, woelki@e3d.rwth-aachen.de

Abstract: This work introduces an innovative approach for the assessment of individual-specific thermal comfort as a part of the so-called human centred closed loop control (HCCLC) platform. The entire system targets on the control of a passenger's thermal comfort instead of the conventionally used air temperatures and solar irradiation of a vehicle cabin. Local thermal comfort of a passenger is evaluated on the basis of equivalent temperatures. The latter are calculated on the basis of body part specific temperature information that are simulated in real-time with the numerical human model MORPHEUS and measured with an infrared (IR) camera. The introduced approach allows to calculate thermal comfort driven dynamic and transient energy requirements of individual body parts at transient, uniform and non-uniform ambient conditions. Corresponding system outputs serve as control signals for decentralized HVAC systems. A robust tracking system for the face region is introduced that is based on an active appearance model (AAM). A central data exchange platform is described, which manages the data exchange between the applied sensor hardware, numerical models and local actuators. It is based on a loose-coupling approach that guarantees the highest possible flexibility with respect to system modularity. In order to be compliant with industrial applications, the system implements a CAN-interface.

Keywords: thermal comfort, human, control, tracking, climatization

1. Introduction

To cope with the challenges that go along with the turnaround in energy policy, several European countries are discussing about the entire replacement of conventional combustion engines by electric drives.

Here, new challenges appear, which are related to the issue between the driving range of the vehicles and the climatization of passengers. Conventional centralized HVAC units use convective heating and cooling to provide thermal comfort for the passengers. However, it is well-known that this technology decreases the vehicle's driving range up to 50 % in the winter case due to the fact that the waste heat of the combustion engine is no longer available and must be entirely provided by the battery (Schmidt et al., 2015). However, an energy efficient and cost effective climatization of passengers can be achieved via decentralized actuators (seat heating, ventilated seats, etc.) that generate local microclimates around the individual.

This work introduces an innovative approach for the control of individual-specific thermal comfort. The entire system was developed to investigate new climatization concepts for vehicles of the future, which put the thermal comfort requirements of human beings in the centre of the control loop instead of using physical quantities such as conventional air temperatures and solar irradiation. In this regard, thermal comfort is assessed on the base of equivalent temperatures. The original approach was modified to calculate the optimal local power demands of individual body parts taking into account gender-related issues, the individual's thermal history and other comfort and physiology-related issues. Corresponding signals can serve as input signals for decentralized HVAC systems.

A fully scalable numerical human model (morphable human energy simulator, MORPHEUS) is used to estimate the human thermoregulatory actions towards inhomogeneous, transient and dynamic climatic effects in real-time (Wölki, 2017). This is achieved by exporting the Modelica-based humanoid as functional mockup unit (FMU) from Dymola for co-simulation (Andersson et al., 2016). Required boundary conditions for MORPHEUS are captured with various sensor hardware.

Contactless optical and thermal infrared sensors are used to assess a passenger's thermal state in real-time. Here, a robust tracking system for the face region is implemented on the basis of an active appearance model (AAM). Individual body segments are tracked, using a randomized decision forest algorithm (Shotton et al., 2013). Furthermore, the separation of the tracking and the detection task offers the advantage of being independent of the thermal resolution of the IR-camera. In order to reduce the temperature measurement errors related to the temperature drift of the camera system, external measurement equipment is used to calibrate the system in real-time. In order to manage the data exchange between the applied sensor hardware, numerical models and local actuators, a central data exchange platform XML is introduced.

2. Materials and methods

Assessment of individual thermal comfort requires the combination of various types of sensors that measure influencing environmental factors.

The HCCLC platform in its entirety is not only depending on various data sources, but also needs to interpret the data by means of mathematical models and communicate with HVAC actuators in order to "close" its feedback loop. The entire platform is based on a software framework that promotes hardware independence and high-level communication between connected hardware and software components. The following gives a brief overview of the architecture and the programming paradigm behind it.

2.1. System overview

The HCCLC platform is designed around a central data server which works as a communication and data storage hub (see subsection 2.3).

Specifically, the data server is used as a proxy between each connected software and hardware component, functioning as a robust abstraction layer between different types of software. Figure 1 shows the system architecture with the data server at its centre. The components communicate via TCP using a well-defined XML schema. The external image processing module is concerned with optical tracking of individuals and thermal temperature measurements (top left corner). The CAN interface is part of the sensor module (bottom left corner). Various numerical models that are used to assess human thermal comfort are part of the computational model component depicted in the top right corner. The latter use a Python adapter to interact with the data server.

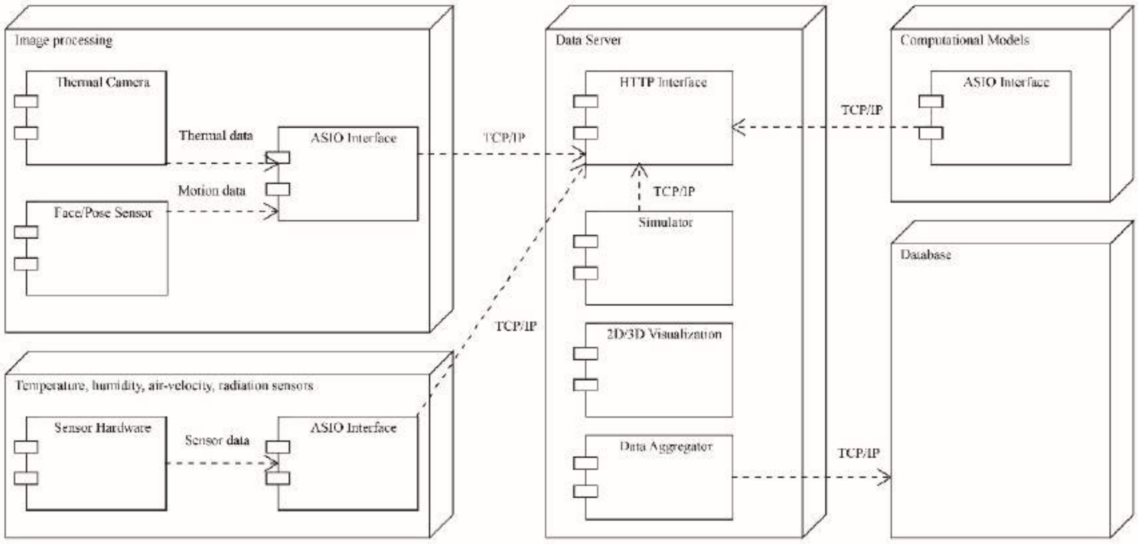


Figure 1. Overview of the system architecture. The system is designed around a central data server which handles communication and data storage (Metzmacher et al., 2017b)

2.2. Data model

The XML schema for interaction between software and hardware components is based on a key-value programming paradigm.

Single data items are referred to as “signals” and consist of a name, which represents the key and a value, which can be any alphanumeric sequence of characters. The same model is also used internally by the data server for temporary data storage. It is implemented as a hash map where the current value of a signal as well as pre-defined meta-data can be queried using the signal name during runtime. Using a key-value approach as opposed to indexed, tabular data is straightforward since the unique key allows for easy addition of measurement points and minimizes the chance of data collision.

2.3. Data server

The data server is the communication hub and data sink of the system. It is a Java based software that accepts data sent by the connected components through simple HTTP requests.

The data server processes standardized XML messages and stores them according to the described data model. Signals communicated by one component can be immediately requested by another component. This allows for bi-directional communication between all connected components. For persistent storage, all communicated data can be stored in a tabular database (usually CSV, direct connection to database management systems is also possible) where each unique signal name is used as the respective column header.

2.4. Image processing and recognition

Thermal image recognition in this work is used to extract skin temperature measurements in a contact-less fashion.

The required software is fundamentally different from software concerned with common temperature sensors, because the image data needs to be processed and algorithmically analysed in order to extract meaningful information. These tasks are combined in the image processing and recognition software component of the system. This work makes use of two distinct tracking algorithms. The first tracking algorithm extracts pose information from a person to accurately identify the position of body regions like face and chest. The second algorithm is concerned with extracting and tracking an accurate face profile of the person. Both algorithms use a depth sensing device mounted beneath the thermal camera in order to ensure independence from temperature differences and quality of the thermal image. The pose tracking algorithm uses a random forest database trained with individual depth images to identify individual poses (Shotton et al., 2013) as its basis and approximates a virtual, three-dimensional face profile so that it matches the face seen by the depth camera (Smolyanski et al., 2014). Here, the face position detected by the pose tracking algorithm is used as a prior.

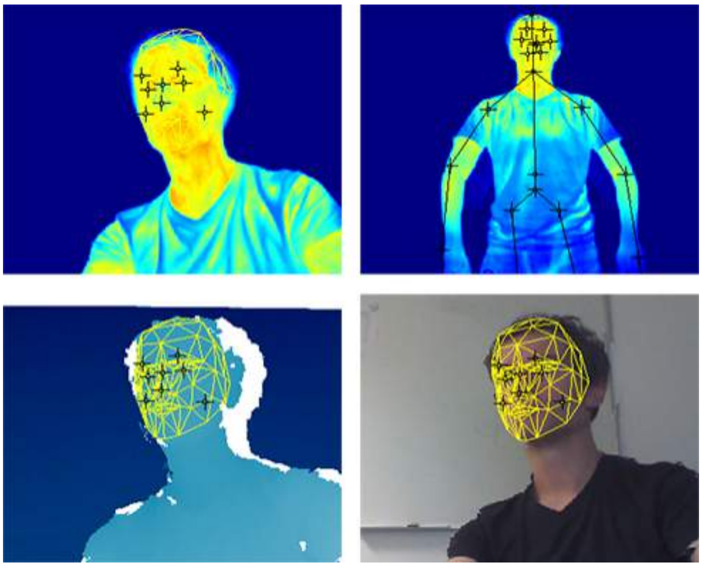


Figure 2. Face and pose tracking

Subsequently, the detected positions can be mapped into the thermal image in order to extract surface and skin temperature values. Thermal radiation values are converted into real temperatures either using internal calibration settings of the thermal camera or reference sensors. The depth image and thermal image are registered in the same coordinate space through previous extraction of intrinsic and extrinsic camera parameters for both, the thermal camera and the depth camera.

Virtual measurement points can be attached to the face or the pose so that each measurement point acts as a virtual sensor representing a region that can be compared with the numerical human model MORPHEUS (see subsection 2.6). Figure **2** shows detected body pose indicators as well as the tracked 3D face along with attached measurement points.

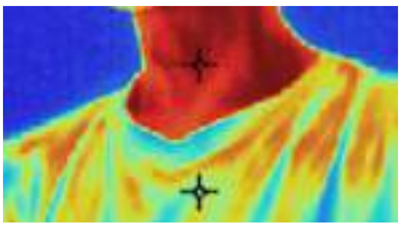


Figure 3. Local surface temperature spots, measured with the IR-camera system at a naked (throat) and a clothed (chest) body location

Figure 3 shows two measurement points used to track local temperature information of the throat and the chest region. The image clearly illustrates the challenges that come along with the assessment of a person’s thermal state via contactless IR-imaging. It illustrates, how clothing layers that cover local body regions can influence measured IR temperature signals due to insulating effects. It further depicts the dependency between local temperature distributions across the body surface and the number of measurement points used to calculate the local temperature information of person. This has to be taken into account, when comparing temperature signals measured by the thermal camera and temperatures simulated with the numerical human model MORPHEUS.

2.5. Visualization

The data server UI has 2D and 3D visualization capabilities, which can be used for direct monitoring of sensor and model data during an experimental evaluation (Figure 4).

This way, the behaviour of computational models can be studied in real-time and erroneous sensor data can be detected early on. Figure 4 shows the 3D view of a sitting person with pseudo colour mappings of energy surpluses and requirements for the head and chest region. The skin temperature is measured using the thermal camera and immediately sent to a thermal comfort calculation algorithm.

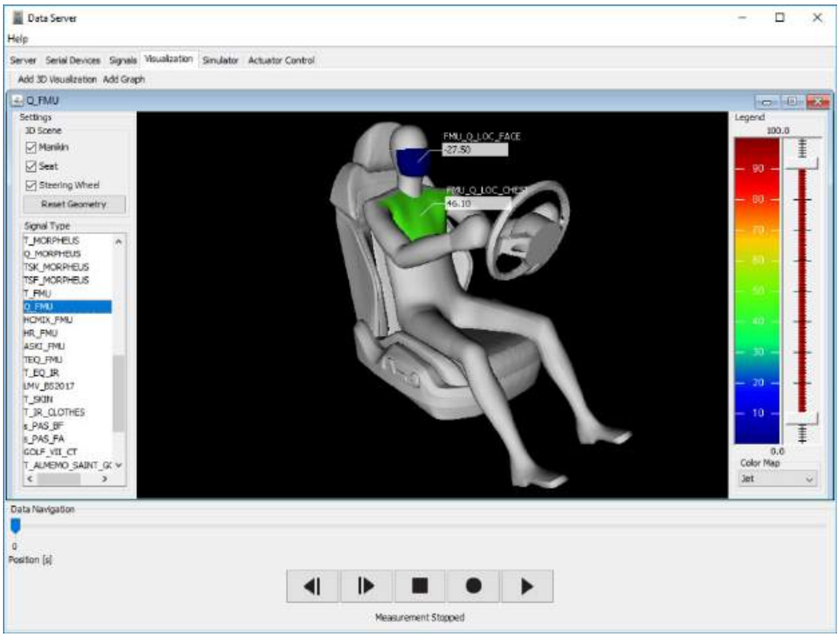


Figure 4. 3D visualization of energy surpluses and requirements at the individual's head and chest region respectively.

2.6. Numerical human model

The numerical human model MORPHEUS is used in combination with the above described code framework of (Metzmacher et al., 2017b) to estimate the body part specific thermal comfort information of persons and the required power that has to be provided by the decentralized HVAC units to keep the local and global thermal comfort of an individual within an acceptable range.

Here, MORPHEUS is used to fill the information gaps for body parts that are hidden from the IR-camera system (e.g. clothing, steering wheel, etc.). The model itself is implemented in the acausal modelling language Modelica and used in combination with the simulation environment Dymola. To enable real-time predictions of the human thermoregulatory response, the entire humanoid was exported as a functional mock-up unit (FMU) for co-simulation (Andersson et al., 2016). A general model overview is given in Figure 5.

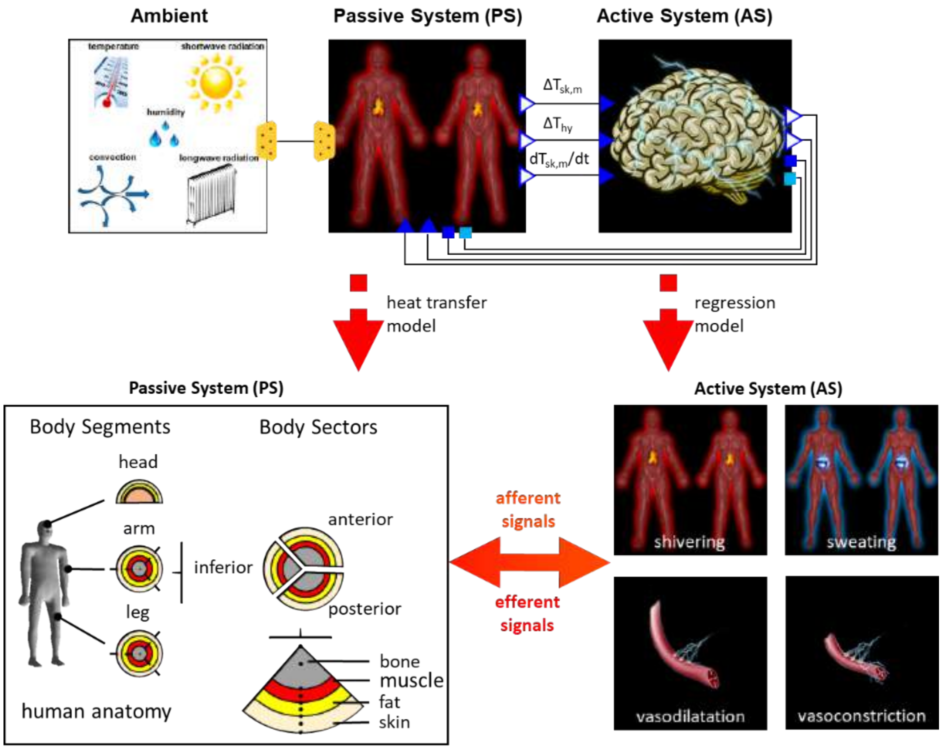


Figure 5. Schematic of the general model concept of MORPHEUS. Black dots inside the tissue layers represent discrete finite volume (FV) nodes within the thermal network (Wölki, 2017)

The basic mathematical model structure of MORPHEUS is inspired by ideas of (Fiala et al. 1999, 2001) and (Tanabe et al., 2002). It is developed in a component-based manner to benefit from Modelica's acausality and code reusability and uses finite volumes (FV) for the spatial discretisation of Pennes' bioheat equation (Pennes, 1948), which describes the transient heat transfer mechanisms that occur in living tissue by the use of the first law of thermodynamics.

The depicted passive system (PS) component contains the geometrical approximation of the human anatomy by the use of 18 cylindrical elements (arms, hands, legs, etc.) and a single half-sphere for the head. Multiple sectors are used to increase the spatial resolution of the model segments with respect to asymmetrical ambient conditions. Each sector is modelled as a combination of seven tissue materials (bone, muscle, fat, skin, lung, brain, viscera) and linked to a central blood compartment that handles the heat exchange between the diverse sectors. To realistically model the cooling of arterial blood streams before they perfuse the tissue layers of the sectors, the blood flow model considers the counter-current heat exchange (CCX) between adjacent arterial and venous blood streams (extremities and shoulders). As a consequence of the arterial blood cooling, the venous blood streams get rewarmed before they return to the central blood compartment, where they form the time-dependent central blood pool temperature.

The heat exchange between MORPHEUS and its physical environment considers convection, radiation, evaporation and respiration and includes the dry and wet heat loss insulation of clothing materials. Here, the evaporation model described in (Fiala et al., 1999) was replaced by the model of (Tanabe et al., 2002), because it provides a much more Modelica-compliant mathematical structure. The active thermoregulatory mechanisms that simulate actions that are elicited by the human central nervous system (CNS) towards disturbances of the body's internal thermal state are embedded in the active system (AS) component (Figure 5). It provides the four active control mechanisms sweating, shivering, vasodilatation and vasoconstriction that prevent the human body from hyper-/hypothermia. The information exchange between AS and PS is modelled via afferent/efferent temperature error signals from the skin and hypothalamus, respectively. In this paper, the anatomical setup of MORPHEUS was designed to represent an average human being with a body fat percentage of 14.44 %, a body weight of 73.50 kg, a heat exchanging surface area of 1.86 m², a basal metabolic rate of 87.13 W, a cardiac output of 4.89 l/min, an overall clothing insulation of 0.6 clo and an activity level of 1.2 met (Fiala et al., 1999).

2.7. Thermal comfort evaluation

Thermal comfort is assessed via body part specific equivalent temperatures (T_{eq}) according to (ISO 14505-2, 2016).

The latter is a common standard that is intensively applied in the vehicle sector for the evaluation of conventional HVAC systems that are based on convective heating and cooling of vehicle cabins. The subjective interpretation of T_{eq} is based on mean thermal votes (MTVs) according to (Nilsson, 2004) and valid for a specific winter/summer case. An MTV is rated with discrete values between +1 (too cold and uncomfortable) and +5 (too warm and uncomfortable) with 3 as the neutral point on a five point Bedford scale.

2.8. Equivalent temperature

In a formal way, T_{eq} [°C] represents the physical temperature of a uniform enclosure, in which a body part experiences the same dry heat exchange (convection and radiation) with its surrounding as in the actual non-uniform scenario.

As specified in (ISO 14505-2, 2016), the appropriate mathematical equivalent is shown in (1):

$$T_{eq} = T_{sf} - \frac{q_c+q_r}{h_c+h_r} \tag{1}$$

Here, T_{sf} [°C] represent the surface temperature of a local body segment, q_c its convective heat transfer [W/m²], q_r its radiative heat transfer [W/m²] and h_c and h_r the corresponding convective and radiative heat transfer coefficients [W/m²°C], respectively.

2.9. Calculation of the body part specific energy requirements

To be able to calculate the necessary power that has to be provided by a decentralized HVAC system in order to get individual body parts into their specific comfort range, equation (1) was modified and rearranged according to (2).

Here, q_{opt} [W] describes the power that has to be applied to a body part, in order to cause optimal thermal comfort, when related to the equivalent temperature $\overline{T}_{eq}$ [°C]. The latter was calculated as the average value of the temperature range specified for an MTV of +3 according to (ISO 14505-2, 2016). In this connection, expression A_{sf} [m²] represents the surface area of a single body part. In this work, it was extracted from the geometrical setup of MORPHEUS.

$$q_{opt} = A_{sf} \cdot (T_{sf} - \overline{T}_{eq}) \cdot (h_{c,mix} + h_r) \tag{2}$$

The heat transfer coefficient $h_{c,mix}$ [W/m²] in (2) is calculated by a mixed convection model that considers both, natural and forced convection (Fiala et al., 1999). The surface temperature T_{sf} is set equal to the simulated surface temperatures $T_{MORPHEUS}$ [°C] as well as to the surface temperature T_{IR} [°C] recorded by the IR-camera system. The idea is to estimate q_{opt} for all body parts, even if they are hidden by obstacles and/or covered with clothing. In this regard, the introduced approach is of special relevance for applications, in which shortage of space and price pressure limit the use of sensor hardware. For the following experiment the face (naked) and the chest (clothed) region were selected for a systematic demonstration of the HCCLC approach. In this regard, $\overline{T}_{eq,face}$ was set to 22.6 °C and $\overline{T}_{eq,chest}$ to 25.3 °C according to (ISO 14505-2, 2016) for the summer case.

3. Experimental setup

The experiment described in this section is an extension of the work described in more detail in (Metzmacher et al., 2017b).

It was performed to investigate the dynamic actions of the human thermoregulatory system with respect to transient changes in ambient conditions and to test the capability of the introduced HCCLC concept regarding its capability to predict local thermal comfort and related power requirements, which can serve as control signals for decentralized HVAC systems. A schematic of the entire setup is shown in Figure 6.

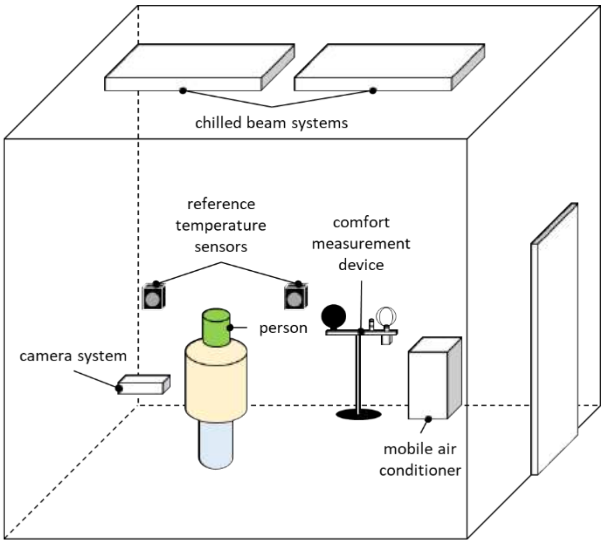


Figure 6. Schematic of the entire experimental setup, redrawn from (Metzmacher et al., 2017)

The figure above shows the camera system, which is positioned in front of the person (1.5 m distance). The reference temperature sensors behind the subject are used for the real-time calibration of the IR-camera system, which significantly improves the measurement accuracy of the recorded local surface temperatures T_{IR}. A comfort measurement device of the German company AHLBORN was used to assess the physical quantities of the ambient such as air temperature and relative humidity (humidity-/temperature sensor FH A646-E1), globe temperature (globe thermometer ZA 9030-FS2), and average air velocity (thermo-anemometer FVA605-TA1O). It was positioned directly beneath the subject, underneath the chilled beam system and outside the detection range of the IR-camera system. This was done to avoid influences of blank surfaces on the temperature measurements of the IR-camera and to limit the convective influence on the HVAC system on the subject as well as the on the humanoid MORPHEUS.

To support the chilled beam system during the cool-down cycle of the experiment, an additional mobile air-conditioner was used. Finally, all the introduced sensor hardware was connected to the HCCLC platform, which is used as the mediator platform that handles the information exchange between sensors and the required numerical models for the calculation of thermal comfort related signals.

4. Experimental design

The experiment in this section was carried out to test the idea of predicting thermal comfort related power requirements for individual body parts, using equation (2).

A transient design was chosen, in order be more compliant with the dominating environmental conditions in vehicle cabins. The study itself was carried out with a single subject. The timing of the test design as well as the operative temperature T_{op} [°C], relative humidity rh [%] and average air velocity v_{air} [m/s] are shown in Figure 7.

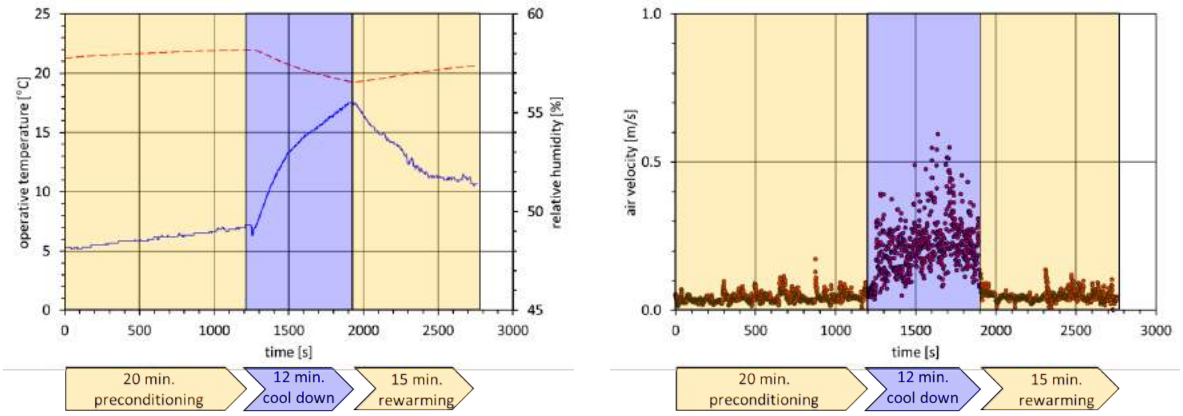


Figure 7. Boundary conditions of the experiment measured at a height of 1.2 m above the floor; dashed line left-hand side: operative temperature (T_{op}), solid line line left-hand side: relative humidity (rh), right-hand side: average air velocity (v_{air})

The experiment started with a preconditioning phase of 20 min. at T_{op} ≈ 22 °C. The latter aims to imitate the so-called "auto-22" setting, which is assumed to provide optimal thermal comfort for the passenger (thermal neutrality) in the automotive sector. It was followed by a 12 min cool-down cycle that reached 19 °C at its lowest point and a 15 min rewarming phase, in which all air conditioning systems were turned off. The depicted physical quantities were recorded at a height of 1.2 m above the floor. This is close to the distance between the ankles and the head of an average person (ISO 7730, 2005).

The ambient conditions depicted in Figure 7 were simultaneously applied to MORPHEUS during the experiment. The latter simulated the thermoregulatory actions of an average human being in real-time as described in subsection 2.6. Furthermore, MORPHEUS was used to estimate body segment specific heat transfer coefficients $h_{c,mix}$ and h_r, the local body surface areas A_{sf} as well as the local heat losses q_c and q_r that are required for the calculation of q_{opt}, T_{eq} and MTV. During the experiment the subject was dressed with a pullover, a t-shirt, jeans, briefs, socks and shoes. This correlates well with an overall clothing insulation value of 1.3 clo (ISO 9920, 2007) and enables the comparison of the measurement and simulation results. The following section contains the results of the experiment for the chest (clothed) and the face (naked) region.

5. Results

The T_{eq} results for the naked face are shown on the left-hand side of Figure 8.

In this connection $T_{EQ,IR,FACE}$ and $T_{EQ,MORPHEUS,FACE}$ were calculated on the basis of equation (1), in which the surface temperature T_{sf} was set equal to the measured IR-temperature T_{IR} and the simulated surface temperature $T_{MORPHEUS}$, respectively. During the pre-conditioning phase of the first 20 min and the final re-warming phase of the experiment, a constant temperature offset of approximately 2 K between both signals can be obtained. The unstable behavior of the $T_{EQ,IR,FACE}$ signal at the beginning of the experiment is related to the initialization phase of the tracking system and can be neglected. During the 12 min cool-down cycle both T_{eq} signals show decreasing amplitudes. In addition, the offset between both signals increases to a maximum of about 3 K. In this regard, $T_{EQ,MORPHEUS,FACE}$ is constantly above the $T_{EQ,IR,FACE}$.

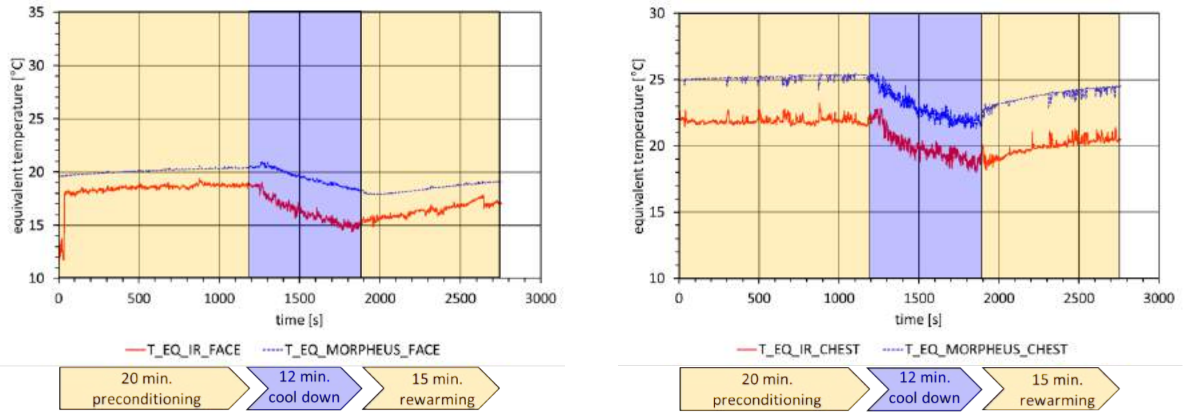


Figure 8. Comparison of the equivalent temperatures (T_{eq}) of the face (left) and the chest (right) region; T_EQ_IR: T_{eq} calculated on the basis of T_{IR}, T_EQ_MORPHEUS_CHEST: T_{eq} calculated on the basis of the simulated $T_{MORPHEUS}$

The comparison of the T_{eq} signals for the clothed chest are depicted on the right-hand side of Figure 8. As for the face, a constant offset between $T_{EQ,IR,CHEST}$ and $T_{EQ,MORPHEUS,CHEST}$ can be obtained throughout the entire experiment, ending up in a maximum difference of 4 K between both signals during the 12 min cool-down cycle. It is interesting to see that both signals show the same signal sequence.

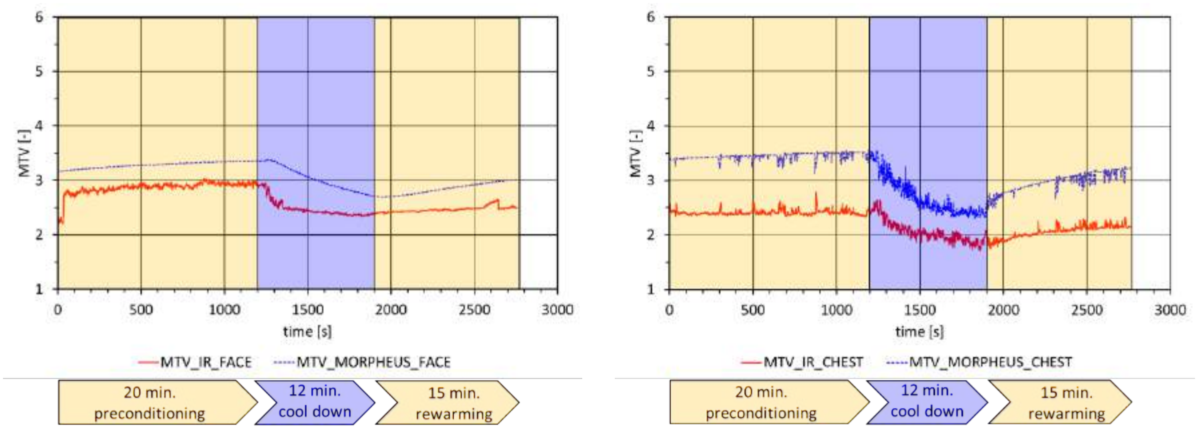


Figure 9. Comparison of local mean thermal votes (MTV) of the face (left) and the chest (right) region; MTV_IR: MTV calculated on the basis of T_{IR}, MTV_MORPHEUS: MTV calculated on the basis of $T_{MORPHEUS}$

The results of the corresponding mean thermal votes (MTV) for the face (left figure) and the chest region (right figure) are shown in Figure 9. For the face region it can be seen that $MTV_{IR,FACE}$ and $MTV_{MORPHEUS,FACE}$ are close to the "neutral" point of +3. Both signals show a nearly constant offset, which again increases during the cool-down cycle. Here, $MTV_{MORPHEUS,FACE}$ slightly fluctuates around the neutral value, whereas $MTV_{IR,FACE}$ strongly tends towards +2, indicating a "cool but comfortable" climatic situation.

The right hand-side of Figure 9 shows the corresponding MTVs for the chest segment. Here, $MTV_{IR,CHEST}$ tends towards a value of +3 (neutral) during the preconditioning phase. During the cool down cycle it stabilizes at a value of +2 (“cool but comfortable”), where it remains even during the rewarming phase. The appropriate $MTV_{MORPHEUS,CHEST}$, however, shows strong tendencies towards a value of +4 (“warm but comfortable”) during the initial 25 min. During the subsequent 12 min it strongly tends towards a value of +3 (neutral), where it stabilizes even during the rewarming phase. In total, this leads to a difference of one scale point between $MTV_{IR,CHEST}$ and $MTV_{MORPHEUS,CHEST}$, where MTVs calculated on the base of $T_{MORPHEUS}$ predict a warmer climatic situation than their counterparts calculated on the basis of T_{IR}.

Figure 10 shows the comparison between the local power requirements q_{opt} for the face and the chest region that were calculated on the basis of equation (2). In this connection, a positive q_{opt} value for the graphs on the left side of Figure 10 indicates a cooling demand, a negative value a heating demand, respectively. It can be seen that the calculated q_{opt} values for the face, which were calculated on the basis of the measured T_{IR} and the simulated $T_{MORPHEUS}$, are in good agreement (Figure 10, left). During the 12 min cool down phase a maximum difference between both signals of approximately 1.2 W becomes apparent. Furthermore, a nearly constant offset of 0.5 W during the preconditioning and the rewarming phase is present.

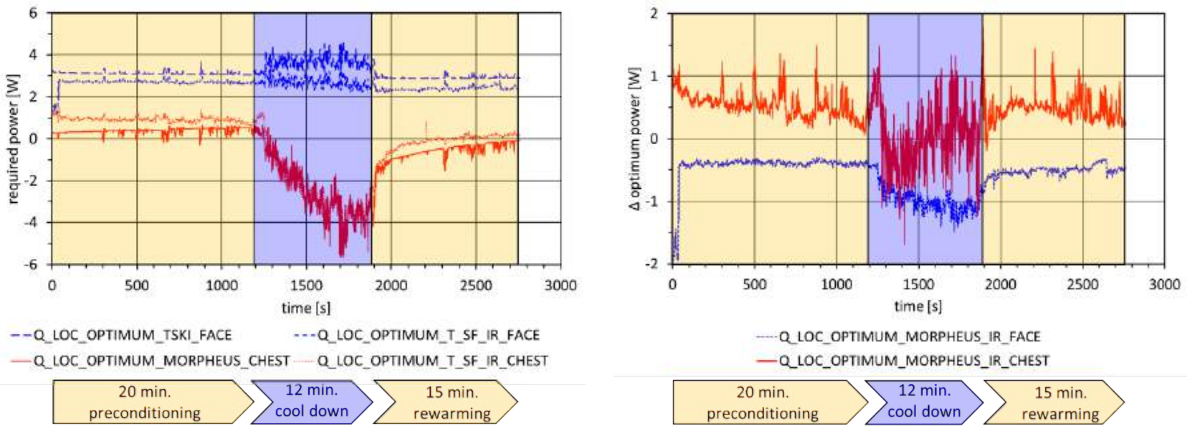


Figure 10. Comparison of the calculated local power requirements (q_{opt}) for the face and the chest region (left). Depiction of the error related to q_{opt} calculated on the basis of T_{IR} and $T_{MORPHEUS}$ for the face and the chest region (right).

The calculated q_{opt} results for the clothed chest region show identical signal sequences for both related signals. Here, $Q_{LOC,OPTIMUM,MORPHEUS,CHEST}$ is constantly below $Q_{LOC,OPTIMUM,TSF,IR,CHEST}$ during the preconditioning and rewarming phase (Figure 10, left). In this regard, Δq_{opt} on the right-hand side of Figure 10 is calculated as $Q_{LOC,OPTIMUM,TSF,IR,CHEST}$ - $Q_{LOC,OPTIMUM,MORPHEUS,CHEST}$. It can be seen that the initial offset of 1 W between $Q_{LOC,OPTIMUM,TSF,IR,CHEST}$ and $Q_{LOC,OPTIMUM,MORPHEUS,CHEST}$ vanishes during the preconditioning phase until the beginning of the cool down cycle (Figure 10, right). In this connection, a maximum difference in q_{opt} for the chest region of - 1.7 W during the first half of the cool down cycle is present, which indicates an increased power demand $Q_{LOC,OPTIMUM,MORPHEUS,CHEST}$, when compared to $Q_{LOC,OPTIMUM,TSF,IR,CHEST}$. However, Δq_{opt} switches during the second half of the cool down cycle, meaning that the $Q_{LOC,OPTIMUM,MORPHEUS,CHEST}$ signal is lower than $Q_{LOC,OPTIMUM,TSF,IR,CHEST}$.

Finally, during the rewarming phase, a maximum difference between $Q_{LOC,OPTIMUM,TSF,IR,CHEST}$ and $Q_{LOC,OPTIMUM,MORPHEUS,CHEST}$ of 1.45 W can be observed (Figure 10, right). It indicates once more that $Q_{LOC,OPTIMUM,MORPHEUS,CHEST}$ is lower than $Q_{LOC,OPTIMUM,TSF,IR,CHEST}$.

6. Discussion

The predicted T_{eq} signals of the face, calculated on the basis of $T_{MORPHEUS}$ (simulated skin temperature of the face) and the measured IR-temperature T_{IR}, show a good match (Figure 8, left-hand side).

The nearly identical dynamic behaviour of those signals, originates from the common base terms that are used together with equation (1). Here, the local heat transfer coefficients h_r and h_c as well as the appropriate local heat flux densities q_r and q_c were provided by the numerical human model MORPHEUS. In this connection, the calculation of h_c represents a possible source of error, thus requiring special attention in the future.

A possible way to obtain the real h_c might be to use a measurement device, which consist of an electric power source that heats up a defined surface area with known material characteristics. The electric power source must be controlled in such a way that there is always a constant temperature difference between the backside and the upper side of the heated surface. The latter is directly exposed to the ambient, thus causing dynamic changes in the corresponding surface temperature as well as in the electric power that must be provided by the power source. Assuming, the electric power is equivalent to the heat flux that is conducted through the surface, allows to perform a local energy balance. It finally enables the calculation of h_c, which in turn can be used as input parameter for MORPHEUS, thus improving the prediction results of the model. Nevertheless, a prior study, in which the described calculation method was compared to objective T_{eq} measurements that were recorded with flat heated sensors (FHS) demonstrated the general correctness of this approach with respect to its dynamic behaviour and T_{eq} range (Metzmacher et al., 2017b).

Furthermore, the steeper gradient for $T_{EQ,IR,FACE}$ at the beginning of the cool down phase indicates a difference in vasomotive reactions and skin blood flow between the average human being represented by MORPHEUS and the real subject (Figure 8, left-hand side). Here, a possible improvement can be achieved by including much more detailed anatomical, physiological and morphological information of the real person in the setup of MORPHEUS. This in turn would influence the predicted skin temperatures as well as the heat exchange between a body part and its surroundings.

Furthermore, prior investigations showed that the temperature distribution across individual body parts is highly inhomogeneous (Metzmacher et al., 2017b). Consequently, this causes high differences between simulated and measured skin/surface temperatures, when selecting inadequate numbers of measurement points for the temperature tracking algorithm. This, however, is another reason for the difference between $T_{EQ,IR,FACE}$ and $T_{EQ,MORPHEUS,FACE}$ (Figure 8).

The right-hand side of Figure 8 once more shows a good match between the simulated equivalent temperature $T_{EQ,MORPHEUS,CHEST}$ and $T_{EQ,IR,CHEST}$, which was calculated on the basis of of the measured T_{IR} of the chest. Even though MORPHEUS uses a virtual clothing model that contains estimations on local clothing insulation values, water vapour permeation coefficients etc., the signal sequences between both signals looks identical. Nevertheless, this represents a possible source of error, which can be reduced by using a multi-objective optimization algorithm for which (amongst others) the clothing insulation might be a possible input parameter. Consequently, this procedure is suggested for T_{IR} and $T_{MORPHEUS}$ of the face as well.

The optimum power (q_{opt}) that must be provided by a decentralized HVAC system for the face and the chest region is shown in Figure 10. In this regard, the applicability of the suggested approach could be demonstrated. It showed a good match between the q_{opt} signals calculated on the base of measured (T_{IR}) and simulated ($T_{MORPHEUS}$) surface temperatures. However, for future applications it is necessary to improve the match between $Q_{LOC,OPTIMUM,TSF,IR,CHEST}$ and $Q_{LOC,OPTIMUM,MORPHEUS,CHEST}$, which can be achieved by the formerly mentioned multi-criteria optimization algorithm, which has to function in real-time.

Finally, even though the approach suggested in this paper seems to be adequate, especially because it is based on a simple measurement of surface temperatures, it can cause trouble when dealing with higher clothing insulation values. In this connection, the insulation value prevents the body heat from being conducted through the clothing layer to the surface, which causes misinterpretations of a person's real thermal state and leads to wrong assumptions with respect to the required q_{opt}. Speaking in terms of a building, this would mean, the measurement of a buildings outside surface temperatures can be used to estimate the thermal comfort of the occupants inside. Nevertheless, further investigations that focus on the applicability of the suggested approach for persons dressed with clothing insulation values outside the defined range of (ISO 14505-2, 2016) will be conducted in the future.

7. Conclusion

This paper presented a highly extensible system that combines software for multi-modal sensor data acquisition, thermal image recognition, robust tracking algorithms as well as a numerical human model to assess human thermal comfort in vehicle cabins.

The highly modular implementation allows to transfer the introduced platform to other domains such as buildings or aircraft cabins. A central data server that is based on a lose-coupling approach manages the data exchange between the sensor hardware and the diverse numerical models in a bi-directional manner. Two methods were introduced that combine a face and pose tracking algorithm with an IR-camera system in order to keep track of body part specific temperature information. The latter were used as input parameters for a thermal comfort assessment model, which was modified in order to calculate the power demand for individual body parts, providing optimum thermal comfort. It was demonstrated that contactless skin/surface temperature measurement in connection with body part specific thermal comfort assessment is a very promising method for the development of energy efficient control strategies for decentralized HVAC systems. However, for body locations that cannot be assessed with the IR-camera systems, because they are covered by objects or clothing layers, a detailed numerical human model represents a necessary complement. This is especially important for higher clothing insulations, where the information of a person's real thermal states is shielded by the clothing material.

Due to this reason, an alternative approach for the calculation of the body part specific power requirements that is based on a physiological modelling approach will be pursued in the future as well. In this regard, the balance comfort model (BCM) of (Schmidt, 2016) will be coupled with MORPHEUS. Here, additional studies are required to improve the prediction quality of the humanoid with respect to individual specific skin and surface temperatures as well as local convective heat transfer coefficients.

8. References

Andersson, C., Akesson, J., Führer, C., 2016. *PyFMI: A Python package for simulation of coupled dynamic models with the functional mock-up interface*. Technical report. Centre for Mathematical Sciences. Lund University

Fiala, D., Lomas, K., Stohrer, M., 1999. A computer model of human thermoregulation for a wide range of environmental conditions: the passive system. *J Appl Physiol*, 87, pp. 1957-1972

Fiala, D., Lomas, K. J., Stohrer, M., 2001. Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. *Int J Biometeorol*, 45, pp. 143-159

ISO 7730, 2005. *Ergonomics of the thermal environment: Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Organization for Standardization*

ISO 9920, 2007. *Ergonomics of the thermal environment: Estimation of thermal insulation and water vapour resistance of a clothing ensemble*

ISO 14505-2, 2016. *Ergonomics of the thermal environment - Evaluation of thermal environments in vehicles - Part 2: Determination of equivalent temperature*

Metzmacher, H., Wölki, D., Schmidt, C., Frisch, J., van Treeck, C., 2017 (a). Real-time assessment of human thermal comfort using image recognition in conjunction with a detailed numerical human model. *Building Simulation 2017: 15th Conference of IBPSA San Francisco 2017*, San Francisco, USA, 07 - 09 August 2017

Metzmacher, H., Wölki, D., Schmidt, C., Frisch, J., van Treeck, C., 2017 (b). Real-time human skin temperature analysis using thermal image recognition for thermal comfort assessment. *Energy and Buildings*, 158, pp. 1063-1078.

Nilsson, H. O., 2004. *Comfort Climate Evaluation with Thermal Manikin Methods and Computer Simulation* Models. PhD. University of Gävle

Pennes, H.H., 1948. Analysis of tissue and arterial blood temperatures in the resting human forearm. *J. Appl. Physiol.*, 1, pp. 93-121

Persson, P.B., 2010. *Physiologie des Menschen - mit Pathophysiologie, Lehrbuch Kapitel 39: Energie- und Wärmehaushalt, Thermoregulation,* 31. Aufl. Springer-Verlag Schmidt, C., Veselá, S., Bidhendi, M.N., Rudnick, J., van Treeck, C., 2015. Zusammenhang zwischen lokalem und globalem Behaglichkeitsempfinden: Untersuchung des Kombinationseffektes von Sitzheizung und Strahlungswärmeübertragung zur energieeffizienten Fahrzeugklimatisierung, *FAT-Schriftenreihe*, 272

Schmidt, C., 2016. *Entwicklung eines Modellansatzes zur Bewertung der thermischen Behaglichkeit unter inhomogenen Klimabedingungen*. PhD. RWTH Aachen University

Shotton, J., Sharp, T., Kipman, A., Fitzgibbon, A., Finocchio, M., Blake, A., Cook, M., Moore, R., 2013. Real-time human pose recognition in parts from single depth images. *ACM*, 56 (1), pp. 116-124.

Smolyanskiy, N., Huitema, C., Liang, L., Anderson, S.E., 2014. Real-time 3D face tracking based on active appearance model constrained by depth data. *Image and Vision Computing*, 32 (11), pp. 860-869

Tanabe, S., Kobayashi, K., Nakano, J., Ozeki, Y., Konishi, M., 2002. Evaluation of thermal comfort using combined multi-node thermoregulation (65MN) and radiation models and computational fluid dynamics (CFD). *Energy and Buildings*, 34, pp. 637-646

Wölki, D., 2017. *MORPHEUS: Modelica-based implementation of a numerical human model involving individual human aspects*. PhD. RWTH Aachen University

Copyright Notice

AFTER DINNER TALK

Economic, social and culture experiences of thermal comfort from field studies in Brazil

Roberto Lamberts

Invited Chair:
Susan Roaf

SESSION 4

Surveys in Hot Climates

Invited Chairs:
Terence Williamson and
Ryozo Ooka

Mixed-mode building with moderately cool temperature and responses of humans

Hitoshi Nagatsugu[1,2] and Pawel Wargocki[1]

[1] International Centre for Indoor Environment and Energy, Civil Engineering, Technical University of Denmark, Kongens Lyngby, Denmark, hitnag@byg.dtu.dk; paw@byg.dtu.dk
[2] Mechanical & Electrical Design Department, Obayashi Corporation, Tokyo, Japan, nagatsugu.hitoshi@obayashi.co.jp

Abstract: To achieve energy saving and efficient business continuity planning (BCP), the number of mixed-mode buildings is increasing. A laboratory experiment was performed to examine human responses in mixed-mode buildings with both natural ventilation and air-conditioning. The aim was to examine whether the mode of operation affects the responses when the physical environment, in particular thermal conditions, were maintained when natural ventilation or air-conditioning were used. The operation modes were simulated in a classroom. Eight subjects participated, each time for 2 hours. They rated environments, their responses and performed tasks selected to simulate office work. In the results, subjects in natural ventilation mode felt air velocity higher than them in air-conditioning mode although it was the same. It was suggested that psychological effects which were caused by the difference of operation of ventilation made votes of thermal sensation, comfort, satisfaction and acceptability in natural ventilation worse than in air-conditioning.

Keywords: thermal sensation, thermal comfort, work performance, laboratory experiment, mixed-mode ventilation

1. Introduction

The energy used for air-conditioning in Japan accounts for about 30% of the total energy use. Therefore, reducing air-conditioning by use of the natural ventilation is directly related to energy saving. Consequently, in the view of energy saving and business continuity planning (BCP) it is proposed to increase number of buildings with natural ventilation. Of course, no use of air-conditioning would be the best aproach to achieve high saving of energy. However, in hot and humid climate like in Japan, it is impossible to avoid using air-conditioning systems for achieving occupants' thermal comfort. Recently, designed natural ventilation is used as one of the methods for energy saving. In this strategy, supply and exhaust diffusers are controlled automatically according to outdoor air conditions, namely, air temperature, relative humidity, air velocity, etc., by central or local monitoring and control systems. This strategy is therefore different from the conventional natural ventilation systems when occupants operate windows manually. If the designed natural ventilation system is not functioning in mixed-mode building, air-conditioning system is in operation. Occupants in mixed-mode buildings experience thus both naturally ventilated and air-conditioned conditions.

In naturally ventilated buildings thermal comfort range is determined by the adaptive comfort model (ACT)(de Dear and Brager, 2002). ACT is constructed based on field measurements in buildings where ventilation was chiefly obtained by windows opened manually by occupants. ACT uses the average running outdoor temperature and the indoor operative temperature, which is adopted by ASHRAE Standard 55. However, it can only be applied to fully non-air-conditioned buildings.

In air-conditioned buildings, the predicted mean vote model (PMV) (Fanger, 1970) is used. PMV is mainly constructed based on static experiments in laboratory where different conditions were created. However there is no special index to evaluate the thermal conditions in mixed-mode buildings, where natural ventilation and mechanical ventilation (including air-conditioning system) operate alternately. This study finally aimed to grasp the optimum environment of occupants in mechanical naturally ventilated buildings. As the first step, human subjective experiments were carried out to investigate the influence of psychological effects on subjective responses, physiological responses and productivity with only air-conditioned mode as a variable.

2. Method

2.1. Facility

The experiments were conducted in a classroom at the Technical University of Denmark, which has a central air-conditioning unit and four operable awning windows. The size of the classroom is 11.2 m by 6.2 m.

2.2. Subjects

Eight subjects (6 males, 2 females) were recruited among the students studying at the University. All of them had lived in Denmark more than one year prior to the start of experiments and they were between 22 and 32 years old. They earned moderate salary and they were in-formed that they would get bonus to keep them motivated. The bonus for the best performing subject was plus 50% of his/her salary and that for the second and the third ones was plus 25% of the salary.

2.3. Experimental scenarios

Two operating scenarios in a mixed-mode building were simulated: natural ventilation mode (NV mode) and air-conditioning mode (AC mode). At first, the experiments in NV mode were carried out. Then the AC scenario was performed four weeks later where the identical thermal environment of the natural ventilation scenario were recreated. All other conditions in classrooms were also kept the same when AC mode and NV mode was simulated. During NV mode the windows were wide open. During AC mode the windows were shut and the air-conditioning system was used to control the conditions indoors.

2.4. Experimental period

Experiments in NV mode were carried out on 3 consecutive days in September in 2017 and experiments in AC mode were carried out on 3 consecutive days in October 2017. The first of the three days both in NV and AC modes were treated as a practice day and were not included in the analysis. All subjects participated when NV mode was simulated and only 7 subjects participated when AC mode was simulated. The data for 7 subjects participating when NV and AC mode were simulated were analyzed. Subjects were asked to wear long pants, t-shirt, long-sleeved shirt (estimated clo of 0.66) in all experiments.

2.5. Measurements

1) Physical measurements

The parameters that were measured are shown in Table 1 and the positions of measurements are shown in Figure 1. Indoor air temperature, relative humidity, illuminance and CO2 concentration were measured in 4 locations and indoor air velocity was measured in 2 locations.

2) Physiological measurements

The parameters measured were heart rate, finger temperature, arterial oxygen saturation (SpO2) and alpha-amylase in saliva. Heart rate was measured with heart rate watch (Fitbit Alta HR, Fitbit corp.). Finger temperature was measured with the radiation thermometer.

Table 1. Parameters of physical measurements

Parameter	Position	Interval[min]	Number of points
Indoor air temperature	0.8m above floor (at desk level)	1	4
Indoor relative humidity	0.8m above floor (at desk level)	1	4
Indoor grobe temperature	1.1m above floor	1	2
Air velocity around subjects	1.1m above floor	1	2
Air velocity around window	1.5m above floor (at window level)	1	4
CO2 conc. around subjects	1.5m above floor (at window level)	1	1
Illuminance	0.8m above floor (at desk level)	1	4

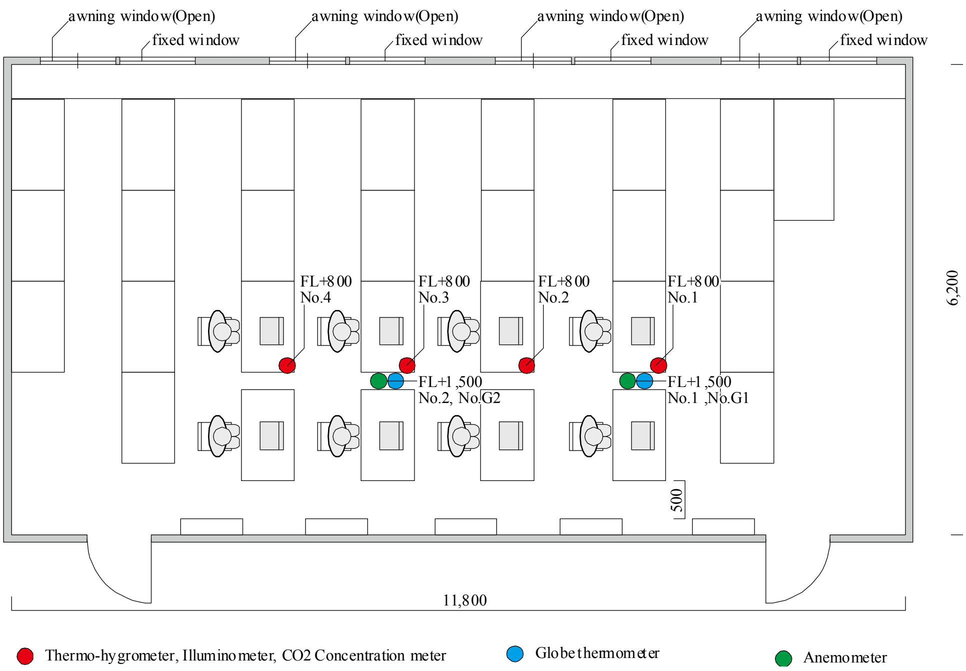


Figure 1. Plan of experimental room and positions of physical measurements

SpO2 was measured with the non-invasive capnographic monitor with the finger sensor. Alpha-amylase in saliva was measured immediately with saliva analyser (Nipro corp.). Finger temperature in-dicates thermal sensation (Lan and Wargocki, 2011). Alpha-amylase reflects stress-related changes in the autonomic nervous system (Nater and Rohleder, 2009).

3) Subjective measurements

The questionnaires were paper-based and contained items measuring thermal sensation, comfort, satisfaction and acceptability, humidity sensation, comfort, satisfaction and acceptability, sensation, and comfort of airflow, satisfaction and acceptability of air quality, sensation and satisfaction of lighting, acoustic and odor environment, comfort, satisfaction and acceptability of working environment, work load, fatigue and intensity of acute health symptoms.

2.6. Work performance task

Three tasks were performed by subjects. They were given 15 minutes to complete these tasks.

Creative thinking task: This task was based on the "Alternate Uses" test developed by Wyon (1996); it was paper-based. In this task, subjects were presented a familiar picture and its name and asked to derive its alternate uses. For example, in the case where the theme was a cup, a cup can be used as a vase beside usual uses for drinking. Each of the creative thinking task used was scored independently across all subjects regardless of the exposure and the time it was taken to complete. The probability of its occurrence was calculated by dividing the number of times it was given by each subject by the total number of subjects. This probability was then used to derive the so-called C-Score. Where;

$$\text{C-Score} = \log_2(1/P) = \log_2(N/n)$$

C-Score = information conveyed by the given name;
P = probability of the name occurrence;
N = number of subjects participating in the experiment;
N = number of times a name was given by different subjects.

Text Typing task: This task was presented on the computer screen. In this task, the subjects were presented a paragraph about 100 words and asked to type it into the text box. Only one paragraph was presented and the subjects typed it repeatedly during the task. Score used in this task was given based on the number of characters typed, which was eventually converted to the score that they can obtain if they performed this task continuously for 1 hour. The number of typing errors were counted.

Addition task: This task was presented on the computer (Toftum et al, 2005). Subjects added 5 two-digit numbers. They were allowed to add the numbers on the paper and write the result on the computer screen. The performance was measured based on the number of correct additions. The score was converted eventually to the score that they can obtain if they performed this task continuously for 1 hour.

Computer-based Tsai-Partington test (Ammons, 1955; Wyon et al.,1979) was presented to subjects to assess their cue-utilization; this tasks was shown in other experiments to correlate with arousal. In this test, the subjects were asked to link 25 randomly selected numbers from 00 to 99 in ascending order in a minute.

2.7. Procedure

The procedure of experiments is shown in Figure 2. Subjects wore heart rate watches (Fitbit HR Alta, Fitbit corp.) all the time during experiments. After putting on the watch, they stayed in the classroom for 20 min to adapt to the created indoor environment. Next then, saliva, finger temperature and SpO2 were measured and subjects answered questionnaires about indoor environment. They then performed three tasks every 15 minutes. After each task, they answered the questionnaires and the heart rate and SpO2 were measured. Tsai-Partington test was carried out for four times. Saliva was sampled before the first task and after the last task. Fatigue and acute health symptoms were rated after the last task.

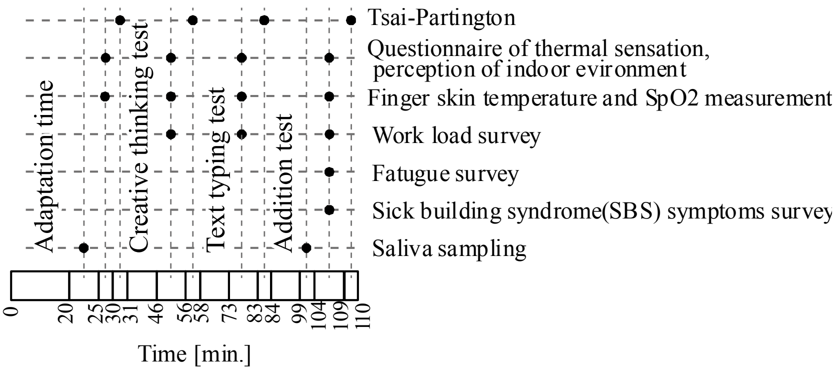


Figure 2. Procedure

3. Result

3.1. Physical measurements

The results of the two modes show table 2. Air temperature in both modes was about 21℃. The difference of air temperature was 0.9℃ but this seems a little influence on thermal sensation in the view of PMV and it was seemed steady during experi-ments. Globe temperature was almost the same as the air one and steady. Relative humidity in NV was about 10% higher but it was thought of a little effect on thermal sensation from the point of view of PMV. Relative humidity in Both modes seemed to be moderate. Air velocity in both modes was almost the same but the its fluctua-tion in NV slightly higher. Illuminance and the CO2 concentration were almost the same. Therefore, it appeared that physical condition of the two modes was almost the same.

Table 2. Mean of physical parameters

	NV		AC	
	mean (min-max)	SD	mean (min-max)	SD
Tair[°C]	21.7 (21.0-22.2)	0.4	20.8 (20.3-21.1)	0.2
Tgrobe[°C]	21.1 (19.9-21.7)	0.5	20.4 (20.1-20.9)	0.1
Relative humidity[%]	56.9 (50.5-63.2)	5.8	47.9 (42.3-53.0)	4.8
Velocity[m/s]	0.069 (0.008-0.131)	0.035	0.080 (0.036-0.134)	0.018
Illuminance[lux]	228 (138-300)	40	223 (148-323)	46
CO2 concentration[ppm]	453 (419-532)	21	454 (411-547)	19

3.2. Physiological measurements

Figure 3 shows the results of finger temperature (a), arterial oxygen saturation (b) and alpha-amylase in saliva (c). Finger temperature decreased in the course of experiments but it did not differ significantly between the two simulated modes. Arterial oxygen saturation was not significantly different between the two modes. Alpha-amylase in saliva was not significantly different between the two modes. Still it was systematically higher in the simulated NV mode.

Figure 4 shows the results of changes in heart rate. Heart rate under two simulated operation modes decreased about 10 bpm from the beginning to the end of experiments. Heart rate was systematically higher in the simulated NV mode in the second half of the experimental period.

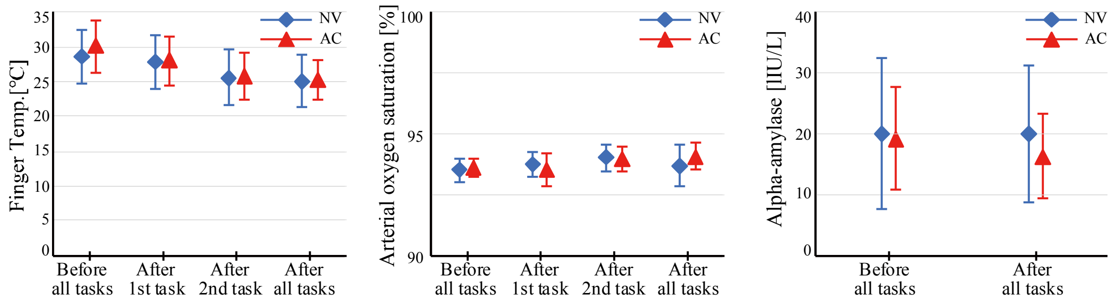


Figure 3. Mean of physiological parameters

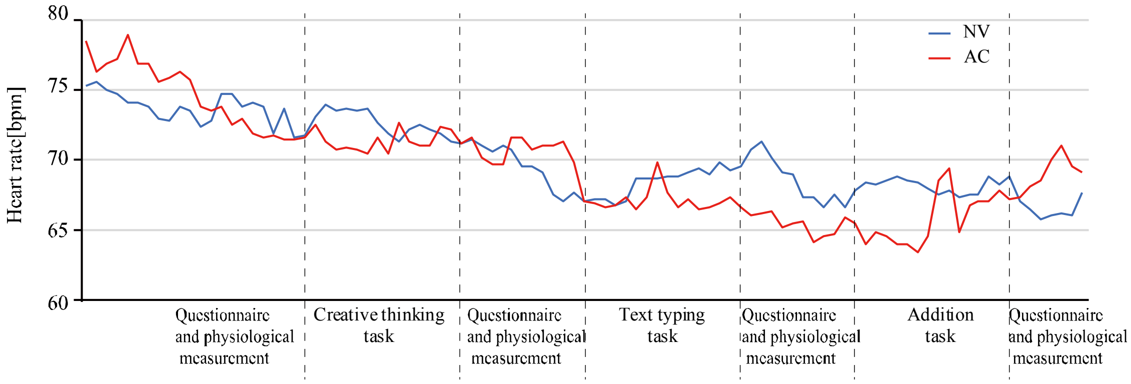


Figure 4. Transition of heart rate

3.3. Subjective measurements

The mean and standard deviation of thermal sensation (a), comfort (b), satisfaction (c), acceptability (d) and sensation of airflow (e) are shown in Figure 5. There was no significant differences in thermal sensation between simulated NV and AC mode. Thermal comfort, satisfaction and acceptability decreased along the course of experiments and the difference in acceptability between the two modes became larger in the favour of AC mode.

Sensation of airflow in NV was higher than in AC mode. There was a significant difference in sensation of airflow rated in the conditions simulating NV and AC mode. Regarding other votes, there were no statistical differences but trends showed that generally the votes in AC were better than NV.

3.4. Work performance

Table.3 shows the scores of each work performance. There were significant differences in performance in addition task. The scores of creative thinking task in NV were higher than in AC, while performance of text typing task and addition was lower.

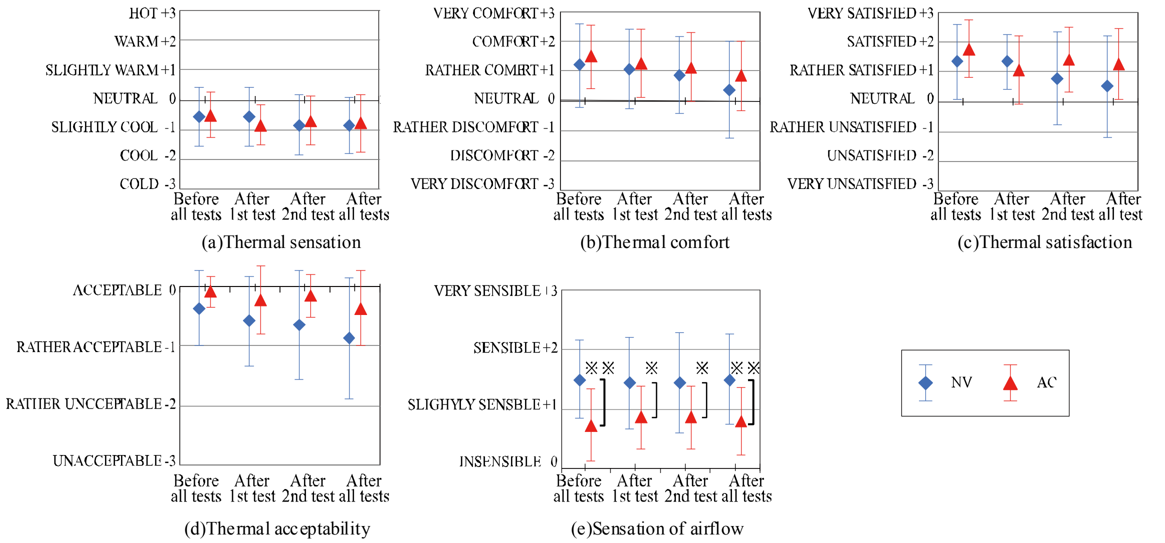


Figure 5. The results of subjective evaluations

※p<0.05, ※※p<0.01 through t-test

Table 3. The results of Work performance tasks

Task		NV	AC	Wilcoxon signed-rank test p-value
Creative thinking	C-Score[-]	9.20	7.73	0.221
Text typing	Number of typing [character/h]	8345	8402	0.975
Addition calculation	Number of attempt answers [attempted/h]	163.1	206.6	0.003

4. Discussion

The subjects reported that they felt thermally slightly cool. There were no difference in thermal sensation when the NV mode (with windows opened) and the AC mode (with windows closed) were simulated. The subjects indicated that their satisfaction with thermal environment was lower when the NV mode was simulated. At the same time they indicated that they could sense the airflow under this condition although measured air velocities did not indicate it to be the case. We consequently infer that thermal dissatisfaction and lower acceptability in the simulated NV mode were probably not caused by the physical conditions but by the psychological effect: Subjects saw that windows were opened when NV mode was simulated and could think that air velocities were higher. We therefore propose that psychological cues could influence the perception of satisfaction and acceptability with thermal environment.

Physiological measurements suggested that subjects felt more stressed when NV mode was simulated in the experimental room. Their amylase levels were higher and heart rate was also higher. The latter is not usually attributed with stress but since their thermal sensation was the same under both conditions studied, it may be inferred that higher heart rate my indicate slightly higher stress (and higher metabolic rate). It is likely that this stress was caused by sensing airflow and dissatisfaction with thermal environment under the condition when NV mode was simulated. At this condition they performed addition task less significantly well and they performed creative task better (which actually was the combination of the recall task and creativity task). The latter task may be considered as more cognitively demanding thus according to Yerkes-Dodson's law (Teigen,1994) it may require higher stress to be performed better. Whether this is the case should be examined in the future.

These results were obtained with few subjects and many of the observations did not reach statistically significant differences. Therefore further experiments are needed to check their validity. The results apply to conditions simulated in the mixed-mode buildings with temperatures around 21°C, i.e. for moderately cool temperatures. Extensions are needed for the conditions with higher temperatures which can be termed moderately warm, say 26°C. The new studies would confirm whether the results observed in the present experiments would hold both with moderately warm and cool temperatures. Furthermore, future studies would suggest a possibility that standards and regulations for achieving comfortable indoor environments can also take into account the method by which the conditions were achieved.

5. Conclusion

Present results imply that the method used to create thermal environment in a room may have significant consequences for comfort responses and work performance. In the present studies, although measured physical environment was not different between the two conditions examined with the simulated NV and AC mode, the responses of subjects were different. We attributed them to psychological responses of subjects to air velocity rather than to perceptions that are attributed to physiological responses.

6. References

Ammons, C. H. (1955). Task for the study of perceptual learning and performance variables. Perceptual and Motor Skills, 5(1), 11-14.

Fanger PO., 1970, Thermal comfort, analysis and application in environmental engineering. Copenhagen, Danish Technical Press.

K.H. Teigen, 1994,Yerkes-Dodson: A Law for all Seasons, Theory&Psychology,Vol 4,Issue 4.

L. Lan and P. Wargocki, 2011: Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance, Indoor Air 2011.

Nater, U.M and N. Rohleder, 2009: Salivary alpha-amylase as a non-invasive biomarker for the sympathetic nervous system: Current state of research, Psychoneuroendocrinology, vol. 34, pp.486–496.

Richard J.de Dear, Gail S.Brager, 2002: Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55, Energy and Buildings, 34, pp.549-561.

Toftum, J. Wyon, D.P., Svanekjær, H. and Lantner, A, 2005: Remote Performance Measure-ment (RPM) - a new, internet-based method for the measurement of occupant performance in office buildings, Proceeding of the 10th International Conference on Indoor Air Quality and Climate, pp.357-361.

Wyon, D.P.,1996: Creative thinking as the dependent variable in six environmental experi-ments: a review, Proceedings of the 7th International Conference on Indoor Air Quality and Climate, Vol.1, pp.419-422.

Wyon D. P., IB Andersen, Funnar R. Lundqvist, 1979: The effects of moderate heat stress on mental performance, Scandinavian Journal of Work, Environment & Health, vol.5, pp.352-361.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Upper limits for thermal comfort in a passively cooled office environment across two cooling seasons

Kit Elsworth[1], Rod Bates[1], Ryan Welch[1], and Billie Faircloth[1]

[1] KieranTimberlake, Philadelphia, USA

Abstract: During two summers in a hot humid climate, an architecture firm conducted a thermal comfort study in a passively cooled office to better the understand the limits of thermal comfort. The office, located in a renovated industrial building in Philadelphia, relied upon natural ventilation, elevated air movement, and desiccant dehumidification for cooling. Thermal comfort surveys were sent to the staff and matched to corresponding ambient temperature and humidity measurements, totalling almost 10,000 survey responses across a 11.5 °C range of indoor temperatures. The overall findings suggest that 80% of the population was satisfied at 28.5 °C and 90% at 27.5 °C. Regression models predict thermal comfort based on indoor temperature and indicate that humidity and clothing did not significantly impact comfort. Occupant clothing insulation (clo) value decreased with temperature from 21 -27 °C, resulting in a minimum clo value of 0.50, including chair insulation, for temperatures above 27 °C. The results show strong agreement with the rate of adaptation in the adaptive thermal comfort model and supports the increase in the comfort threshold given 1.0 m/s of elevated air movement. The findings from the continuous observations of an occupant population across two summers allow for validation of the adaptive thermal comfort model and support design strategies that can maintain comfort over a large range of indoor thermal conditions.

Keywords: thermal comfort, adaptive thermal comfort, field study, longitudinal study, passive cooling

1. Introduction

Professional office environments historically operate within a narrow, uniformly applied temperature band (ASHRAE, 1992) (ISO, 1994). Offices are mechanically conditioned to ensure temperatures consistently fall within this band throughout all workspaces, including desks, conference rooms, and support spaces, permitting human bodies to achieve homeostasis given workplace-appropriate clothing and typical metabolic rates for sedentary activity. These assumptions are reflected in the first indoor thermal comfort standard developed in the late-1960s (Fanger, 1967) (Fanger, 1973), which rationalized human thermal comfort as a heat balance equation based on findings from a comfort chamber study. Subsequent field studies challenged this equation, finding indoor thermal comfort varies by climate, culture, and behavior (Humphreys, 1976). This opened a new era of thermal comfort where researchers sought to show that humans' ability to thermally adapt is influenced by various social and behavioral factors, ultimately leading to the development of the ASHRAE adaptive thermal comfort model (de Dear & Brager, 1998). The adaptive thermal comfort model states these social and behavioral factors, along with past thermal history, modify the thermal preferences of building occupants such that individuals' thermal preferences depends on season and climate. Research has found building conditions that align with the adaptive comfort model result in more satisfied occupants under a wider range of indoor conditions (de Dear & Brager, 1998). Therefore, this standard has become the basis for the design of passive cooling strategies.

Given the current demand for carbon neutral buildings, architects and engineers have motivation to evaluate the effectiveness of passive conditioning for professional office environments (AIA, 2018). Thermal comfort field studies are a crucial method of evaluation because they capture individual perception and adaptation to real world conditions, accounting for cultural constraints and diurnal swings - factors difficult to integrate into controlled climate chamber studies or broad post occupancy evaluations, demonstrating that the adaptive comfort model better defined comfort. (Nicol & Roaf, 2005). Researchers previously used field studies to compare the effectiveness of adaptive comfort theory and passive cooling to the design standards of various climate zones (Nicol, et al., 1999) (Indraganti & Rao, 2010). Many field studies found that when occupants are allowed to adapt, they maintain thermal comfort above code-required set points (Karyono, 1995) (Malama, et al., 1998) (Chan, et al., 1998) (Wagner, et al., 2007) (Luo, et al., 2015).

The multivariate nature of thermal comfort field studies in office environments make them difficult to execute and interpret. Researchers have limited access to building sites and survey participants over a prolonged duration. Despite office environments generally supporting seated workers performing light tasks, the transferability of results can be challenged by differences in climate zone, building volume or floor area, furniture type and arrangement, and proximity to building features, such as air diffusers or windows. Furthermore, employees are often required to adhere to office policies that assist or deter individual adaptation, such as dress codes, seat assignments, work schedules, and degree of personal control over personal environment such as the opening or closing of a window or the use of a desk fan. The totality of these factors must be considered when designing a field study, collecting data for it, and transforming insights into actions that can be taken by building designers, owners, and managers.

Here we present results from a longitudinal field study of a passively-conditioned professional architecture office located in Philadelphia, Pennsylvania (USA). The two-story, 6,300 m^2, masonry building was originally constructed in 1949 as a beer bottling factory. A deep retrofit in 2015 converted the building into an open office with physical and digital fabrication studios. The main office component is located on the second floor, which features a 12 m tall ceiling and a clerestory row of north, south, and west facing windows as well as a north to south central roof monitor. The retrofit intended to obviate the need for mechanical, chiller-based cooling, which led to the implementation of a passive, naturally ventilated conditioning system.

The building and its inhabitants provide a unique setting, free of typical field study constraints, for research on passively conditioned professional office environments and human adaptation. The architecture firm approached the retrofit as an experiment, including the selected conditioning systems and spatial planning details. The firm anticipated and planned a multi-season field study which commenced in spring 2015, shortly after occupancy. A small team of the firm's architects and researchers assumed responsibility for building controls and implemented an active management approach. Throughout the study period, the team collected and interpreted data to inform management protocols, such as advisories to the building's inhabitants, logic statement adjustments, and modifications to building systems. The firm's office policies encouraged rapid human adaptation during the cooling season, permitting casual dress, mobility across the office, and flexibility of work schedule. Participants in the study were incentivized through self-interest and commitment to the mission of sustainability with the knowledge that the study may advance practices within the architectural profession.

This field study involved occupant surveys and indoor environmental measurements collected over the summers of 2015 and 2016. The findings are used to address the following questions: For a professional office environment implementing passive conditioning strategies, what is a reasonable temperature limit of human thermal comfort? What percentage of office workers are satisfied, or alternatively dissatisfied, under these conditions? And which variables contribute to satisfaction and dissatisfaction? This long-term study offers valuable insight into the experiences of individuals attempting to maintain comfort during a daily routine. These findings can be shared with practitioners to encourage experimentation and used to improve the design and implementation of passive strategies in new construction. These findings may also be used to refine design standards or thermal comfort models that predict thermal comfort under hot and humid conditions in office environments.

2. Methods

2.1. Building Operations

The building integrates a variety of passive strategies to optimize occupant comfort while minimizing energy use (Figure 1). The passive strategies include night flushing, stack ventilation, and natural ventilation. The night flushing process relies on the monitor fans to draw 17 m^3/s of air into the building through the building's windows on the north, south, and west facades. Stack ventilation, achieved through closing the office level windows and exhausting air through the central monitor windows, leverages natural buoyancy and is used when exterior temperatures, humidity, or dust levels make natural ventilation undesirable. When exterior conditions are appropriate, natural ventilation is achieved by opening the windows on the north, south, and west sides of the building envelope. During the cooling season, locally driven cooling efforts included occupant controlled 1 m diameter industrial floor fans and 5 Watt personal desk fans capable of moving air at approximately 1.0 m/s at the occupants' position. This air speed was the maximum air speed measured with a hot-wire anemometer (Kanomax A044 0.10-30 ±0.015 m/s) at heights of 0.1 m and 1.1 m with all fans active. In addition to the passive measures used to cool the building, the office minimizes solar heat gain throughout the summer via interior roller shades with 10% openness on the south and west windows.

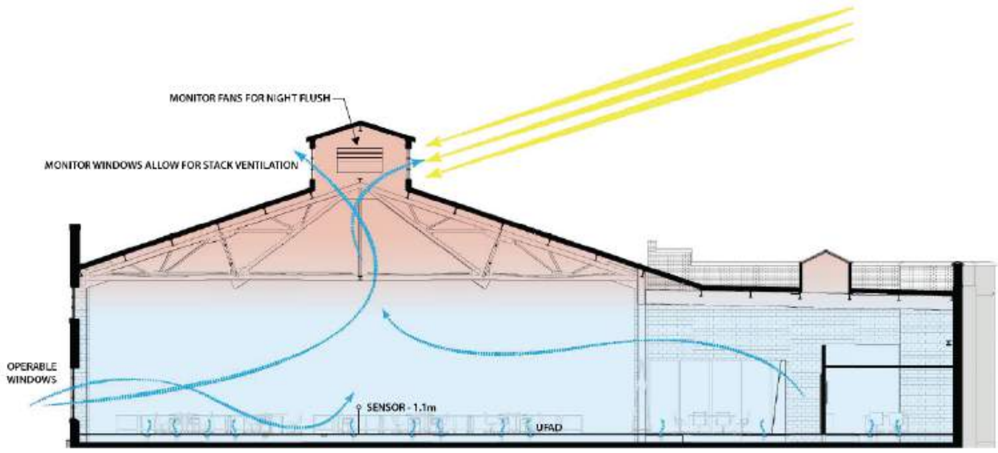


Figure 1. An east-west building section showing airflow under natural ventilation. The building's tall open office allows for stratified air to accumulate at the top of the space and easily exhausted via operable monitor windows.

Mechanical ventilation was delivered via an underfloor air distribution (UFAD) system with local control by occupants, enabled with a manually actuated swirl diffuser located near each desk. The UFAD system's supply air, a mix of outdoor air and indoor return air, was latently cooled with a 15-ton liquid desiccant dehumidification system. During the study's first month, the building underwent a commissioning exercise to determine the best passive operational sequence, resulting in highly variable interior conditions. The daily sequence of night flushing followed by natural or stack ventilation, as appropriate, ultimately became the building's normal routine during the study period.

2.2. Sample

The 26-week study period began with 98 participants and by its conclusion grew to 130, 60% of whom were male and 40% were female. Due to the variations in office attendance, attributable to hiring, travel, vacation, or illness, the number of participants varied daily. While the study did not monitor daily occupancy, the accuracy of the study's calculated participation rates was improved using the office vacation and travel calendars to account for the members of the study population known to be out of the office. This method resulted in a more dynamic and accurate assessment of the study participation than would have been achieved by assuming the total number of current employees present in the office was constant.

2.3. Surveys

The thermal comfort study was conducted using surveys emailed as a hyperlink to the entire office staff every weekday at 10:00 AM and 4:00 PM. These times were chosen to fall well within typical arrival and departure times to capture the greatest number of responses and avoid any effect of increased metabolic rate resulting from participants' morning commute. The web-based survey form (Figure 2) consisted of four questions: Employee ID, Attire, Thermal Sensation, and Location. Employee IDs were collected to determine each individual's weekly response rate and participation across the study period. The Attire question consisted of a dropdown list of ten representative clothing assemblies from which the participant could select the outfit that most closely resembled their attire. This list covered of a broad range of clothing insulation values ranging from a sleeveless dress (0.31) to a jacket, pants, and a long-sleeve shirt (0.99). The total clo value for each clothing assembly was calculated using the University of California, Berkeley's Center for the Built Environment's Comfort Tool, including a 0.10 increase in overall clo value to account for insulative value of office chairs (Hoyt, et al., 2013). In addition to the Attire question's dropdown list, the Thermal Comfort question was presented as a radio button list reflecting the Bedford 7-point scale (Bedford, 1936). Lastly, the Location question took the form of an interactive office floorplan that allowed participants to select the workstation or room from which they were taking the survey.

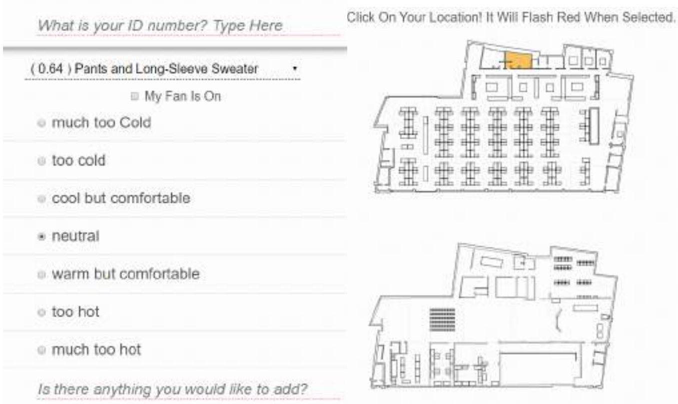


Figure 2: Thermal comfort survey form and screenshot of location selection on office floorplan.

Following the initial 26-week study, a separate 10-week survey was administered to understand the participants' typical metabolic rates. This second web-based survey was formatted and administered in a manner similar to the initial survey, but also required participants to indicate the highest activity level they experienced in the past 20 minutes. This activity question presented participants with a dropdown list of options representing a variety of activities including sitting, walking, standing, biking, running, and working in the office's fabrication studio.

2.4. Sensor Hardware

Concurrent with the thermal comfort surveys, a network of sensors recorded the second floor workspace interior temperature and relative humidity in five-minute intervals at three locations throughout the main office level (Figure 3). Each sensor consists of an analog humidity sensor with a ±3% manufacturer's stated accuracy and a 1-Wire integrated circuit with an in-chip temperature sensor that has a ±0.5 °C manufacturer's stated accuracy. Each sensor is housed in custom 3D-printed casing with a stainless-steel mesh enclosure that shields the technology from radiation and dust while still permitting airflow.

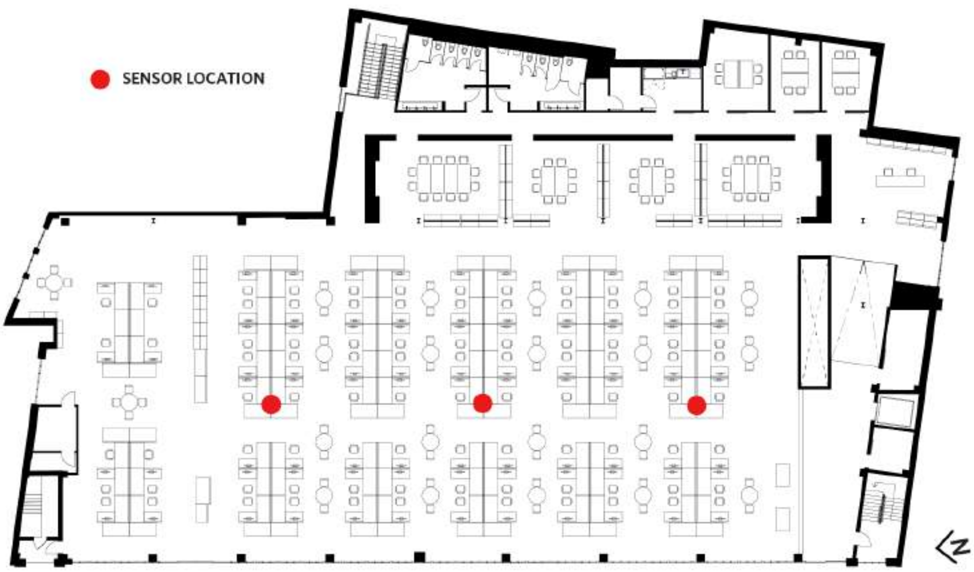


Figure 3: Floor plan of the office showing location for the three ambient temperature and humidity sensors, mounted at 1.1 meters above the finished floor.

The sensor locations were selected as representative indicators of the air temperature and relative humidity in the building's occupied zones. Since no significant differences between the readings of these three sensors were found during the study period, recorded temperatures at each measurement interval were averaged and used to match survey responses. Consequently, all further use of the term "interior air temperature" refers to the average of these three simultaneous sensor readings.

During periods in which the sensor network was unable to transmit or record sensor data, average indoor environmental data from the building management system (BMS) was used to impute these instances. The BMS communicates with five thermostats located across the office, all of which meet ASHRAE 55-2013 Section 7.3.5.2 requirements since they record temperature with an accuracy of ±0.5 °C and relative humidity with an accuracy of ±2%.

Outdoor temperature was also recorded in five-minute intervals by a rooftop-mounted climate monitoring station (± 1.1 °C at 0.1 °C resolution and ± 5% RH at 1% resolution).

2.5. Statistical Analysis

The Chi Squared test was used to determine significance across the range of environmental conditions and survey votes. Multiple linear regression was used to fit the data of this study and produce a formula for comfort given the variables of air temperature, humidity, and clothing. A logistic regression determined the probability for officewide comfort given the indoor air temperature. Bootstrap resampling provided cross-validation of the multiple linear regressions, performing a 100-fold cross validation test for the regression model using a 70% training set (Kuhn, 2008). For every cross-validation, the Mean Square Error (MSE) and coefficient of determination (R^2) were calculated and the standard deviations were recorded to understand variances in model performance.

3. Results

This thermal comfort field study amassed an extensive dataset that includes both survey and sensor measurements. With a dataset of 9,889 survey responses collected along with indoor environmental measurements collected between 2015 and 2016, many possible topics of study emerge. This specific analysis attempts to determine the limits of thermal comfort in a passively conditioned environment, the factors that influence thermal comfort, and a reasonable temperature limit for a passively conditioned professional work environment.

3.1. Survey Statistics

To determine whether the survey dataset is representative of the office population, response and participation rates were calculated on a weekly basis for both summers, with individuals who responded at least once during the week being counted as participants. Across the whole study, the average response rate was 39%, of which 47% of the responses were submitted by females and 53% were submitted by males. Compared to the ratio of females to males in the office, this result indicates that women chose to respond to the survey more frequently.

Table 1: Survey statistics for 2015 and 2016. Average response rate across the study was 39%, while an average of 73% of individuals participated on a weekly basis.

	2015	2016	Total
Start Date	May 25	May 23	-
End Date	Sept 9	July 25	-
Total Weeks	16	10	26
Surveys Sent	13,688	11,431	25,081
Survey Responses	6,375	3,514	9,889
Male	3,419 (54%)	1,799 (51%)	5,218 (53%)
Female	2,956 (46%)	1,715 (49%)	4,671 (47%)
Mean Response Rate*	46%	31%	39%
Mean Participation**	76%	68%	73%
Male	57%	53%	56%
Female	43%	47%	44%

* Total number of weekly surveys sent divided by the total number of weekly surveys submitted

**Percent of individuals who responded at least once per week to the daily surveys

Results from the metabolic rate survey showed that 93% of participants were either sitting (81%) or standing (12%) before or during completion of the survey. Only 7% reported walking, while less than 1% reported running, biking, or working in the fabrication studio. Due to the minimal difference in metabolic rates between seated (1.2 MET) and standing work (1.4 MET) (ASHRAE, 2013) , as well as the large percentage of seated and standing participants in the survey database (93%), these data were not parsed for metabolic rate.

3.2. Indoor and Outdoor Environmental Conditions

During the study, maximum and minimum daytime indoor air temperatures during occupancy spanned from 21.5 to 33 °C. Overall, an average day's temperature gain in the office was 4.5 °C as the building warmed from an average low of 24.5 °C to an average high of 29 °C. However, the occasional heat wave resulted in several instances where indoor temperature peaked between 29-31 °C and on occasion eclipsed 32 °C. Corresponding relative humidity values were between 25% and 80%, translating to a dewpoint range from 4.5-23.5 °C.

Despite fluctuating significantly, the building's indoor climate did not experience the same extremes as the outdoor environment. The full range of exterior temperature and humidity levels depicted in Figure 4 show outdoor temperatures as high as 36 °C and recorded dewpoints as high as 27 °C. Contributing to this difference in indoor and outdoor temperatures and humidity levels was the building's dehumidification system, as well as the ability to close the building's windows when outside conditions were warmer than those found indoors.

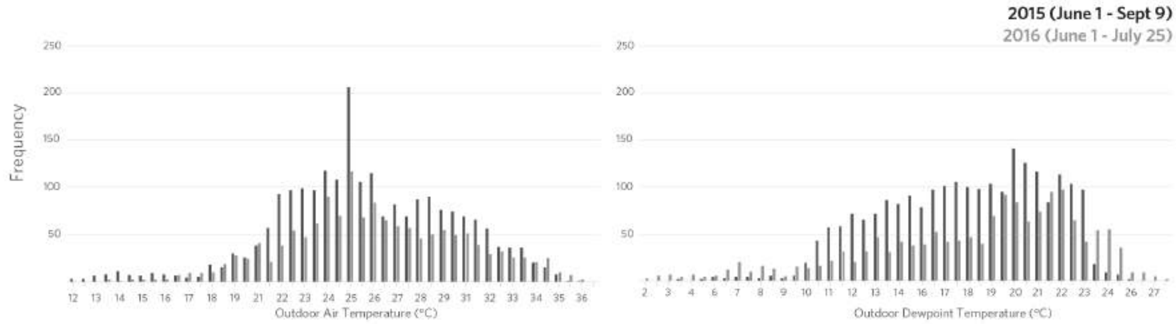


Figure 4: Outdoor air temperature and dewpoint distribution for 2015 and 2016.

The average outdoor temperatures and dewpoints between the two years only differed by 0.05 °C and 0.3 °C, respectively. The small difference in the outdoor temperature and humidity data between the study's two summers indicates that both years experienced similar climatic conditions and produced consistent exterior climatic conditions, allowing the two summers to be combined for an aggregated analysis on thermal comfort. To ensure the accuracy of on-site sensor readings, the data recorded by the rooftop-mount climate station during the study's two summers was compared, validated, and found to be consistent with simultaneous data from Philadelphia International Airport.

3.3. Thermal Comfort Profile – Temperature and Humidity

Categorical thermal comfort responses were plotted according to temperature and relative humidity (Figure 5). The pronounced lateral gradient in this scatter plot suggests temperature was the primary factor influencing participants' thermal comfort, while the absence of a vertical gradient suggests that relative humidity had little effect on comfort. For example, survey responses corresponding to indoor temperatures between 25-29 °C show participants were comfortable regardless of relative humidity levels, which ranged from 25-75%. Humidity's limited influence on participants' perceived comfort is most likely due to the office's increased elevated air movement, an explanation that is consistent with previous research that shows air movement to increase occupants' humidity tolerance (Zhai, et al., 2015) (Melikov, et al., 2008). Furthermore, the European standard EN15251 found that humidity has a small impact on thermal sensation when developing the European adaptive thermal comfort model (Nicol & Humphreys, 2010).

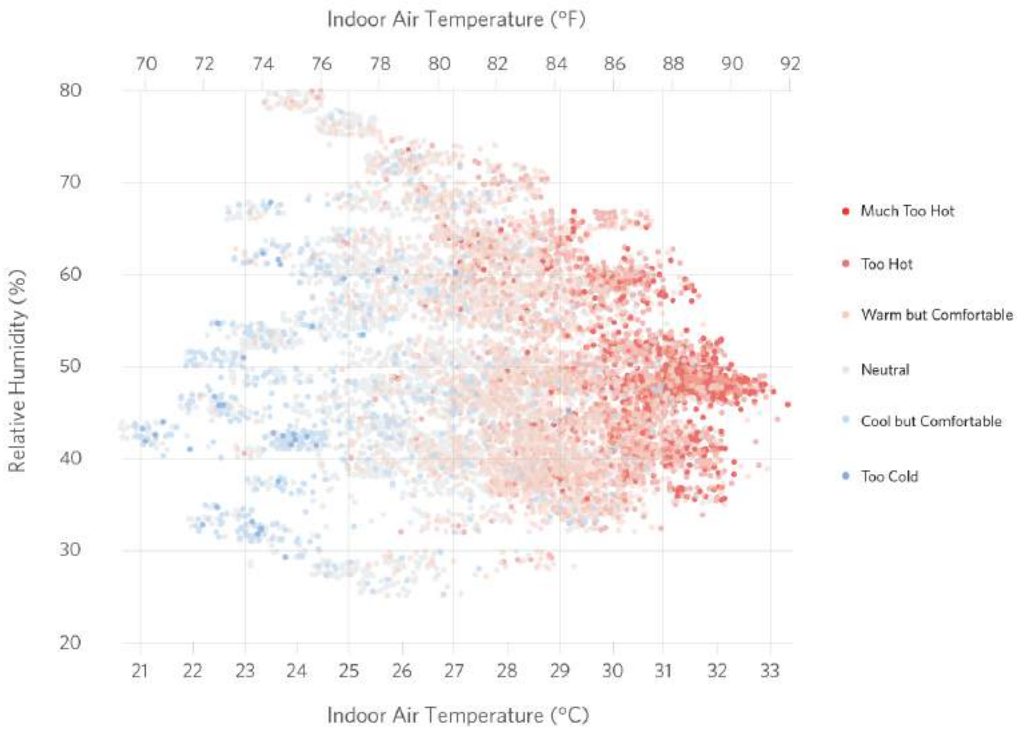


Figure 5: All survey responses against corresponding indoor temperature and relative humidity.

To determine the relationship of temperature, humidity, and clothing on thermal comfort, a multiple linear regression was produced. Each variable was centered and scaled to allow for weighting and comparison of all predictor variables. These results are shown in Table 2.

Table 2: Comparison of coefficients from centered and scaled multiple linear regression.

Variable	**Coefficient**	**Std. Error**	**p-value**
Indoor Temperature (°C)	0.635	0.009	p < 0.001
Indoor Dewpoint (°C)	0.112	0.009	p < 0.001
clo	-0.030	0.008	p = 0.001
Intercept	4.784	0.008	p < 0.001

$$TC = 0.265\, T_{in} + 0.032\, T_{dp} - 0.416\, clo - 2.96 \qquad (1)$$

The regression equation for thermal comfort using temperature, dewpoint, and clo is summarized in Equation 1, where *TC* represents the seven-point thermal comfort vote, T_{in} represents the indoor air temperature (°C), T_{dp} represents the indoor dewpoint (°C), and *clo* represents the respondent's clothing insulation value. For all predictor variables, the standard error was less than 0.009 and p-value less than 0.001. The regression coefficients in Table 2 validate the belief that temperature has the greatest impact on comfort due the large weighting of the coefficient with respect to the other predictor variables. The small coefficient corresponding to indoor dewpoint reinforces the belief demonstrated in Figure 5 that dewpoint does not greatly affect thermal comfort. It is surprising that an increase in clo value will decrease the thermal comfort vote, suggesting that occupants were more comfortable with more layers of clothing. This result may be influenced by the discomfort experienced by individuals wearing low levels of clothing on hot days, thus experiencing discomfort due to indoor conditions and not clothing choice. The negative clothing coefficient may reveal that a general correlation exists with occupant comfort and higher clothing levels at hotter temperatures. However, this should not be considered causation since the small coefficient suggests the impact is minimal, estimating an increase of 0.1 clo results in a 0.04 decrease in thermal comfort vote.

The regression model in Equation 1 resulted in MSE of 0.58 and a R^2 of 0.46, which match with the statistics of a cross-validated model, showing a strong representation of typical conditions. The 100-fold cross-validation yielded an average MSE of 0.58 ±0.008 and R^2 of 0.47 ±0.010. The low standard deviation reflected in this figure indicates the model has a low variance and high repeatability.

3.4. Thermal Comfort Profile – Population Satisfaction

Comfort is defined as thermal comfort votes including *Cool but Comfortable*, *Neutral*, and *Warm but Comfortable*. More than 95% of the office population expressed comfort at temperatures below 27 °C (Figure 6). Between 27 and 32 °C, the population's comfort decreased somewhat linearly, demonstrating temperature's significant effect on thermal comfort (chi squared $p<0.05$). When temperatures exceeded 31.5 °C, thermal comfort did not vary beyond 20-30% of the office being comfortable.

ASHRAE 55-2013 recommends a building's mechanical systems be designed to provide 80% of the population with comfortable conditions. Based on the results of this study, a building owner operating a building with similar passive measures wishing to adhere to this threshold should aim for a setpoint temperature of 28.5 °C. Reducing this average temperature by only 1 °C to 27.5 °C, however, would result in 90% occupant comfort. Additionally, air temperatures below 22 °C may cause cool discomfort.

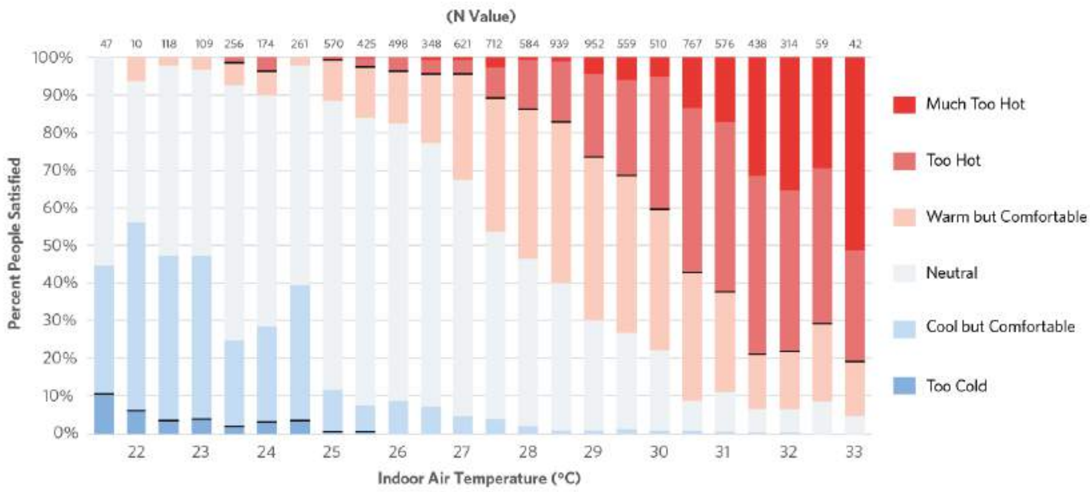


Figure 6: Less less than 80% of the population was comfortable when temperatures exceed 28.5 °C.

The comfort votes were converted into a binary variable to perform a logistic regression to determine the statistical structure of the comfort curve due to warm discomfort.

$$P_c = \frac{e^{(23.1-0.76\,Tin)}}{1+e^{(23.1-0.76\,Tin)}} \qquad (2)$$

Where T_{in} as indoor air temperature (°C) and P_c as the probability that the vote is comfortable. The logistic regression represented in Equation 2 can be used to accurately predict the probability for comfort within the population given the indoor air temperature in the passive environment studied here. The curve of this regression roughly follows the path of the black lines in Figure 6.

3.5. Clothing

Equation 1 shows clo value has minimal effect on thermal comfort but examining clo value against temperature offer insights into the choices of clothing across indoor conditions. Over the course of the study, the average clo value was 0.51 ±0.07 (N=9,889), including the 0.10 clo added for chair insulation to all responses. These clo values are on the lower end of other longitudinal case studies, which found average summer clo to range between 0.5 and 0.55 (Schiavon & Lee, 2013) (Honnekeri & Pigman, 2014). Removing the contribution of the chair, the actual clo value for the clothing assembly alone produces a median value of 0.41. This value is more indicative of the typical clo value of occupants observing a flexible dress code in an office environment in the summer.

The participants' clo values were plotted against indoor temperature, showing only votes indicating comfort to remove any instances when clothing, rather than temperature or humidity, may have been the source of discomfort (Figure 7). This same graph also includes the average clo value during each recorded indoor air temperature, as well as a 95% confidence curve. The graph's regression line shows that the rate of clo value decline decreases from 21 °C to 27 °C. Above 27 °C, a clo value of 0.50 was maintained, exhibiting the minimum clo value preferred in this office setting. Interestingly, this regression curve performs opposite in nature to the decrease in population comfort in Figure 6. While clo values decline until 27 °C, the percentage of comfortable participants in Figure 6 remains constant. Above 27 °C, clo values reach a steady minimum value as comfort percentage decreases. It suggests that 27 °C serves as an inflection point for both clothing and overall satisfaction, a trend that indicates that, above 27 °C, individuals are not able to reduce clothing and dissatisfaction will increase.

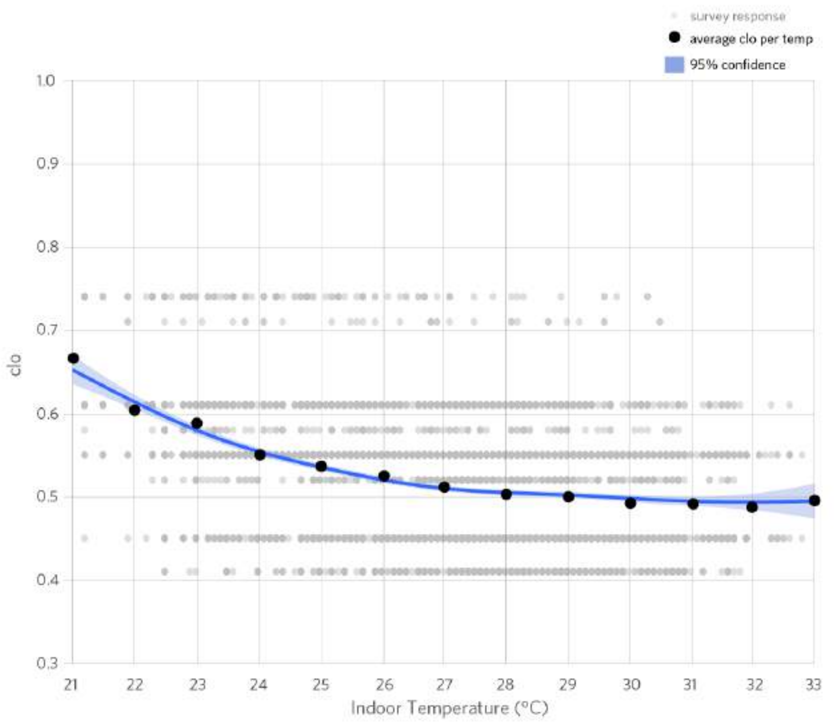


Figure 7: The average clo values decrease until temperatures reach 27 °C. At temperatures above 27 °C, clo values reach a steady minimum value of 0.50.

4. Discussion

4.1. Comparison with the Adaptive Comfort Model

Following the study's analysis, the authors calculated the optimal indoor air temperature per prevailing outdoor mean temperature, defined as the arithmetic average of the previous seven days' mean daily outdoor temperature. The purpose of this calculation was to compare survey results to the ASHRAE adaptive thermal comfort model. Despite not having the means to measure globe temperature during the study, spot measurements across the study's two seasons with a Kestrel 5400 Heat Stress Meter (accuracy 0.5°C dry-bulb, 1.5°C globe temperature) found minimal difference between the globe temperature and indoor air temperature. Consequently, indoor air temperature rather than operative temperature was used during the adaptive comfort calculation.

While it is simple and straightforward to calculate the neutral temperature, or optimal comfort temperature, of this study (26.6 °C), this single metric does not capture the full range of temperatures at which a population will feel thermally neutral. As described by Nicol and Humphreys (Nicol & Humphreys, 2010), the neutral temperature in a variable climate becomes a "moving target" and changes as individuals adapt to their environment. Therefore, regressions to determine neutral temperature based on prevailing outdoor mean temperature dataset are provided in Equation 3 (R^2=0.50).

KieranTimberlake Study: $$T_{in/op} = 0.26T_{out-mean} + 20.0\ (°C) \quad (3)$$

ASHRAE Adaptive Comfort Model: $$T_{op} = 0.31T_{out-mean} + 17.8\ (°C)$$

(Schilling Brager & de Dear, 2000)

Where T_{op} is operative temperature (˚C) and $T_{out\text{-}mean}$ is the seven-day average outdoor monthly mean temperature (˚C). When compared with the regression used to define the adaptive thermal comfort zone, the coefficient for operative temperature differs only by 0.05.

The equivalency of the outdoor monthly mean slopes suggests the adaptive thermal comfort zone predicts that humans will adapt to warmer temperatures to a greater extent than the individuals in this study. This may be due to the influence of a global population on the ASHRAE adaptive thermal comfort model rather than a sample from a single city. However, due to the intercept, this study's regression line trends slightly above the adaptive comfort zone's neutral temperature, indicating a greater threshold of comfort (Figure 8). The offset is due to the intercept value from this dataset, which occurs approximately 2.2 ˚C above the adaptive comfort zone's neutral temperature when outdoor mean is equal to zero. Within the temperatures experienced in the indoor environment, this offset is between 1.0-1.8 °C . This increase in the upper limits of comfort is similar to the increased threshold for comfort allowed by the adaptive comfort model when 0.9 m/s of air movement is provided, as per ASHRAE Standard 55-2013. This air speed is found to be roughly equal to the 1.0 m/s of air movement experienced at the occupant's seated position under the influence of fans and can be seen as evidence to validate the increase in thermal comfort preference attributed to elevated air speeds of approximately 1.0 m/s.

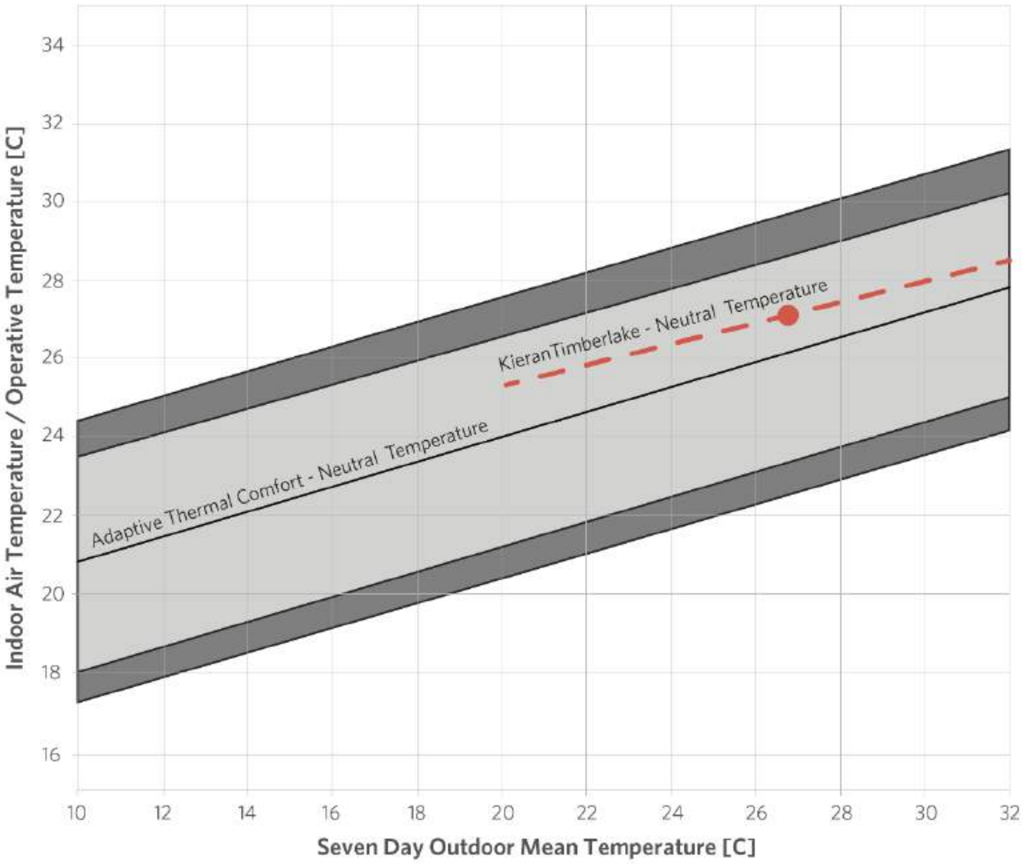


Figure 8: A graph plotting the optimal indoor temperature for a range of outdoor prevailing mean temperatures showings the study's comfort limits are approximately 1.0-1.8 °C greater than the adaptive thermal comfort model.

Although this study only allowed for the submission of discrete clo values, the results showed that the rate of clo value declined slower than predicted in the adaptive clothing model. The adaptive thermal comfort model estimates the median clo value will decrease 0.1 clo for every 2 °C increase in indoor temperature (de Dear & Brager, 1998). In this study, the rate of decline in clo value between 21 and 27 °C was found to decrease at a rate of 0.1 clo per 4.5°C indoor air temperature. This rate declined as temperature increased as occupants gradually reached the minimum clo value, 0.5, experienced in the office.

4.2. Measurement Limitations

It should be recognized that this study is not without limitations, but these limitations are opportunities to improve future data collection. For one, it was not possible to continuously monitor air speed during the study. Instead, air speeds were measured using an anemometer spot measurements. While these measurements were representative of the predominant air speed felt by survey participants, it is possible that individuals seated near windows or close to floor fans experienced a greater air velocity.

Globe temperature was also not measured continuously. Although the authors are confident that the MRT based on envelope and equipment gains was approximately equal to the building's indoor temperature, the impact of direct solar was not captured. The building's direct sun exposure through monitor windows is transient on any given day, but its presence may have overlapped with the time in which participants completed their daily surveys.

Lastly, one of the greatest challenges during data collection was tracking the survey's participants. Without the ability to track daily occupancy, the office's population was estimated each week using office-wide vacation and travel calendars. A more accurate method of tracking building occupancy will improve the calculation of survey participation rate for future research.

4.3. Examining Standard Survey Metrics

During this study, the authors discovered constant communication with survey participants was the most effective way to maintain survey participation. However, the study also found that participants' interest declined over the study period, indicating some level of survey fatigue. ASHRAE 55 suggests using response rate to determine the efficacy of a survey and whether the survey reached a representative sample size. The challenge with relying on response rate as a measure of success is that response rate is not indicative of nonresponse bias or survey fatigue, both of which are additional metrics that longitudinal surveys should consider. Likewise, closely tracking survey fatigue allows future researchers to decide whether to remind participants to complete surveys or to conclude their study. In addition, administrators conducting longitudinal surveys should understand nonresponse bias not only in individuals but in spatial distribution. A spatially distributed set of responses across a building will ensure that the dataset is not representative of a single zone or floor.

ASHRAE 55-2013 provides recommended response rates for thermal comfort studies based on three population sizes. For populations greater than 45 people, response rates should exceed 35%. However, this standard does not differentiate between transverse and longitudinal surveys, nor does it provide guidance on calculation methodology. Other standards, such as ASHRAE's Performance Measuring Protocol (ASHRAE, 2010) dictate a 40% response rate. In both instances, the calculation methodology is not disclosed in the standards, an omission that invites a generous interpretation of this survey metric. This room for interpretation is significant, especially when considering that calculating response rates on a daily, weekly, monthly, or cumulative basis can yield significantly different results. When conducting a study-wide analysis, longitudinal surveys with weeks of low participation can seem valid by accounting for a high response rate at the outset of the study. Alternatively, tracking individual response rates at a granular scale, for example per survey issuance or by day, can allow the survey dataset to be reliably normalized and may justify exclusion of survey responses that are not representative of the whole population.

There is an opportunity to improve longitudinal survey protocol and analysis with data driven findings. The survey fatigue experienced in the 2016 portion of this study offers a unique opportunity to identify the minimum required response rate or test other analytical methods that can produce similar, statistically significant results. In addition, resampling the dataset may also serve as another means to artificially lower the response rate and examine its effect on the study's outcome. In this study, the close agreement of MSE and R^2 between the regression and the resampling along with the low standard deviation indicated a high repeatability and demonstrated confidence that the survey dataset did not suffer from nonresponse bias.

5. Conclusions

Over the course of two summers in a hot and humid climate, 90% of the population was comfortable at 27.5 °C in a passively cooled office environment. When indoor air temperatures rose to 28.5 °C, 80% of the building's population remained thermally comfortable. Indoor air temperature was found to be the most influential predictor of comfort, while humidity and clothing had little impact. Participants' clo values decreased in response to temperature until indoor temperatures reached 27 °C, at which point the average clo value maintained 0.5 clo.

This field study validates the adaptive thermal comfort model under elevated air movement by demonstrating that the thermal neutrality line occurs 1.0-1.8 °C greater than the adaptive comfort model when providing 1.0 m/s of air speed to occupants. These results confirm the applicability of the adaptive thermal comfort model in passively cooled modern office buildings where occupants have operable windows and access to fans.

Acknowledging that research on such high indoor temperatures and humidity levels is difficult to conduct, it is the authors' intent for this study to demonstrate the full range of thermal comfort in a passively cooled office space in a hot and humid climate. Although the design of the study could not quite achieve 100% comfort during the summer, the ability to provide passive cooling for a majority of the season may encourage designers to move toward mixed-mode designs that reduce reliance on air conditioning within reasonable limits. In addition, the authors hope this study will empower building owners to survey their own populations, using the resulting data to determine how best to reduce cooling demand while maintaining occupant comfort.

6. Acknowledgements

This study was the vision of Stephen Kieran and James Timberlake, who provided the facility and access to staff, in addition to guidance and encouragement. The KieranTimberlake staff deserve recognition for their participation in the surveying to research human thermal comfort in a contemporary office setting. Jason Niebish and Paul Worrell deserve credit for their hard work managing the building during this study. Alex Knipe was instrumental to the survey's development. The authors would also like to acknowledge the support of Ed Arens and Stefano Schiavon from the University of California, Berkeley's Center for the Built Environment for their insightful comments and suggestions.

7. References

AIA, 2018. *The 2030 Committment.* [Online] Available at: https://www.aia.org/resources/6616-the-2030-commitment [Accessed 12 January 2018].

ASHRAE, 1992. *ANSI/ASHRAE Standard 55-2013, Thermal Environmental Conditions for Human Occupancy,* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE, 2010. *Performance Measurement Protocol for Commercial Buildings.* Atlanta: American Society of Heating, Refrigerating and Air Condition Engineers.

ASHRAE, 2013. *ANSI/ASHRAE Standard 55-2013, Thermal Environmental Conditions for Human Occupancy,* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Bedford, T., 1936. *The Warmth Factor in Comfort at Work. A Physiological Study of Heating and Ventilation.* London: Medical Research Council Industrial Health Research Board.

Chan, D., Burnett, T., de Dear, R. & Ng, S., 1998. A large scale survey of thermal comfort in office premises in Hong Kong. *ASHRAE Technical Data Bulletin,* Volume 14, pp. 76-84.

de Dear, R. & Brager, G., 1998. Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions,* 104(1), pp. 145-167.

Fanger, P., 1967. Calculation of thermal comfort, Introduction of a basic comfort equation. *ASHRAE Transactions,* Volume 73, pp. 4.1-4.20.

Fanger, P., 1973. Assessment of man's thermal comfort in practice. *Occupational and Environmental Medicine,* 30(4), pp. 313-324.

Honnekeri, A. & Pigman, M., 2014. *Use of Adaptive Actions and Thermal Comfort in a Naturally Ventilated Office.* IndoorAir Conference PrePrint.

Hoyt, T., Schiavon, S., Piccioli, A., Cheung, T., Moon, D. & Steinfeld, K., 2013. *CBE Thermal Comfort Tool.* [Online] Available at: http://cbe.berkeley.edu/comforttool/

Humphreys, M., 1976. Field Studies of Thermal Comfort Compared and Applied. *Journal of the Institution of Heating and Ventilating Engineers,* Volume 44, pp. 5-27.

Indraganti, M. & Rao, K. D., 2010. Effect of age, gender, economic group and tenure on thermal comfort: A field study in residential buildings in hot and dry climate with seasonal variations. *Energy and Buildings,* 42(3), pp. 273-281.

ISO, 1994. *International Standard 7730, Moderate thermal environments - Determination of the PMV and PPD indices and specifications of the conditions of Thermal Comfort,* Geneva: International Standards Organization.

Karyono, T. H., 1995. Thermal comfort for the Indonesian workers in Jakarta. *Building Research and Information,* 23(6), pp. 317-323.

Luo, M. et al., 2015. Evaluating thermal comfort in mixed-mode buildings: A field study in a subtropical climate. *Building and Environment,* Volume 88, pp. 46-54.

Malama, A., Sharples, S., Pitts, A. & Jitkhajornwanich, K., 1998. Investigation of the thermal comfort adaptive model in a tropical upland climate. *ASHRAE Transactions,* Volume 104, pp. 1194-1206.

Melikov, A., Kaczmarcyzk, J. & Sliva, D., 2008. *Impact of air movement on perceived air quality at different level of relative humidity.* IndoorAir. Copenhagen. 2008., pp. 17-22.

Nicol, F. & Humphreys, M., 2010. Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Building and Environment,* Volume 45, pp. 11-17.

Nicol, F., Raja, I., Allaudin, A. & Jamy, G. N., 1999. Climatic variations in comfortable temperatures: the Pakistan project. *Energy and Buildings,* 30(3), pp. 261-279.

Nicol, F. & Roaf, S., 2005. Post-occupancy evaluation and field studies of thermal comfort. *Building Research and Information,* 33(4), pp. 338-346.

Schiavon, S. & Lee, K. H., 2013. Dynamic predictive clothing insulation models based on outdoor air and indoor operative temperatures. *Building and Environment,* Volume 59, pp. 250-260.

Schilling Brager, G. & de Dear, R., 2000. A Standard for Natural Ventilation. *ASHRAE Journal.*

Wagner, A. et al., 2007. Thermal comfort and workplace occupant satisfaction—Results of field studies in German low energy office buildings. *Energy and Buildings,* 39(7), pp. 758-769.

Zhai, Y. et al., 2015. Human comfort and perceived air quality in warm and humid environments with ceiling fans. *Building and Environment,* Volume 90, pp. 178-185.

Effects of environmental perception on thermal sensation in sub-tropical and high-density cities: a case study of Hong Kong

Mona Sum Ching Chung[1] and Kevin Ka Lun Lau[1,2,3]

[1] Institute of Future Cities, The Chinese University of Hong Kong, Hong Kong, scchung@cuhk.edu.hk;
[2] CUHK Jockey Club Institute of Ageing, The Chinese University of Hong Kong, Hong Kong
[3] Institute of Environment, Energy and Sustainability, The Chinese University of Hong Kong, Hong Kong

Abstract: Outdoor thermal comfort is crucial in sub-tropical regions where summer heat stress impede outdoor space usage. Research on the effects of environmental perception on thermal comfort has increased in recent years as a result of intensified urban development and it has been found that urban geometry design can modify the relationship between climate and thermal comfort. Despite this, there is a lack of holistic studies focusing on the effects of qualities of urban space on thermal adaptation and comfort. This study investigates the relationship between environmental perception and outdoor thermal comfort under typical summer conditions in streets and parks in Hong Kong by conducting questionnaire survey on thermal sensation and environmental perception in terms of convenience, visual and acoustic comfort, air quality and safety. Simultaneous micrometeorological measurements were also conducted to obtained objective conditions of thermal comfort in designated urban spaces. A total of 1921 responses were collected between June 2017 and September 2017 in 12 locations. Overall, we found that environmental perceptions, particularly the perceived air quality, acoustic comfort and visual comfort, significantly affect thermal sensation and comfort. Improved perception of each investigated environmental parameter could lead to a substantial increase in the percentage of people feeling thermally comfortable.

Keywords: Outdoor thermal comfort, thermal adaptation, environmental perception, hot humid climate, urban design

1. Introduction

Thermally comfortable outdoor spaces are essential as they provide places for people to gather, interact and carry out outdoor activities. It is particularly important in sub-tropical countries where high temperature can lead to discomfort and thus decrease the time spent outdoors and increase heat-related health risks (Johansson and Emmanuel, 2006, Yang et al., 2013). Previous studies revealed that microclimatic parameters strongly affect thermal sensations. There have been several attempts to quantify the effect of each microclimatic parameter on human thermal comfort. Though there has not been a solid conclusion of which of these parameters are the most important, it is generally believed that air temperature and radiative temperature are the most significant factors in the subtropical regions because wind speed and relative humidity are stable throughout the year (Lin et al., 2011). However, in a study on different European countries, relatively weak correlations have been found between subjective thermal evaluation and single microclimatic parameters alone which suggest that this approach may not be adequate when it is applied in outdoor environment (Nikolopoulou and Lykoudis, 2006). As such, thermal indices (e.g. Physiologically Equivalent Temperature (PET), Standard effective temperature (SET)) which account for multiple parameters are commonly used to study the relationship between objective and subjective thermal evaluation (Johansson et al., 2014).

Despite the importance of microclimatic parameters, they are found to only contribute to around 50% of the variance in subjective thermal comfort evaluation (Nikolopoulou and Steemers, 2003). This has resulted in the study of thermal adaptation including physical (e.g. by changing the environment or one's metabolic heat), physiological (long-term acclimatization due to repeated exposure to a stimulus) and psychological adaptations (change in perception due to 'information' they have for a situation). It is suggested that urban design could play a role in the psychological adaptation of outdoor space users and be able to increase their thermal tolerance (Nikolopoulou and Steemers, 2003). For instance, Hirashima et al. (2016) showed that under the same thermal conditions, people were more thermally tolerant in a square with scenery of green areas, water features, natural sounds (e.g. birds) and low rise historical buildings, as oppose to another square surrounded by high-rise buildings, heavy traffic and no water features. Similarly, a study found that green environment was perceived as most thermally comfortable, followed by water environments, and built environments were perceived as neutral (Klemm et al., 2015).

While there is increasing evidence for the ability to increase thermal tolerance with urban design, it is necessary to evaluate and quantify the impacts of different qualities of urban space on human thermal comfort in order to strategize urban planning. Thus, instead of site specific comparisons in terms of thermal comfort, this study focuses on the impact of various qualities of an outdoor space. This study aims to investigate the relationship between subjective thermal comfort and the perception of qualities of outdoor space in terms of convenience, visual comfort, acoustic comfort, air quality and safety under typical summer conditions in Hong Kong, as thermal discomfort commonly occurs in sub-tropical summer.

2. Methodology

2.1. Study Area

Hong Kong is one of the most densely populated cities in the world, with a population density of 6,780 persons per square kilometre and a total population of nearly 7.2 million in 2016. It is located at 22°15'N 114°10'E and has a subtropical monsoon climate. Summertime in Hong Kong (May to September) is typically hot and humid, with 80% of the total annual rainfall during this period. Summer 2017 was unusually hot and wet with a mean daily maximum temperature of 31°C and a record breaking daily maximum temperature of 36.6°C preceding the strike of Typhoon Hato. As thermal discomfort in subtropical regions commonly occurs in summer, our study was performed on hot, sunny days between June and September 2017.

Hong Kong has a diverse urban environment and a total of 12 sites were selected to carry out the field campaign in order to capture a wide range of environment. The study sites (figure 1) include residential areas of different urban density (two high density public housing estates, and a low density residential area), street environments in areas of mixed purpose (residential and commercial) and the financial and business hub in Central, as well as urban park (Hong Kong Park) and pier (Central Pier) environments.

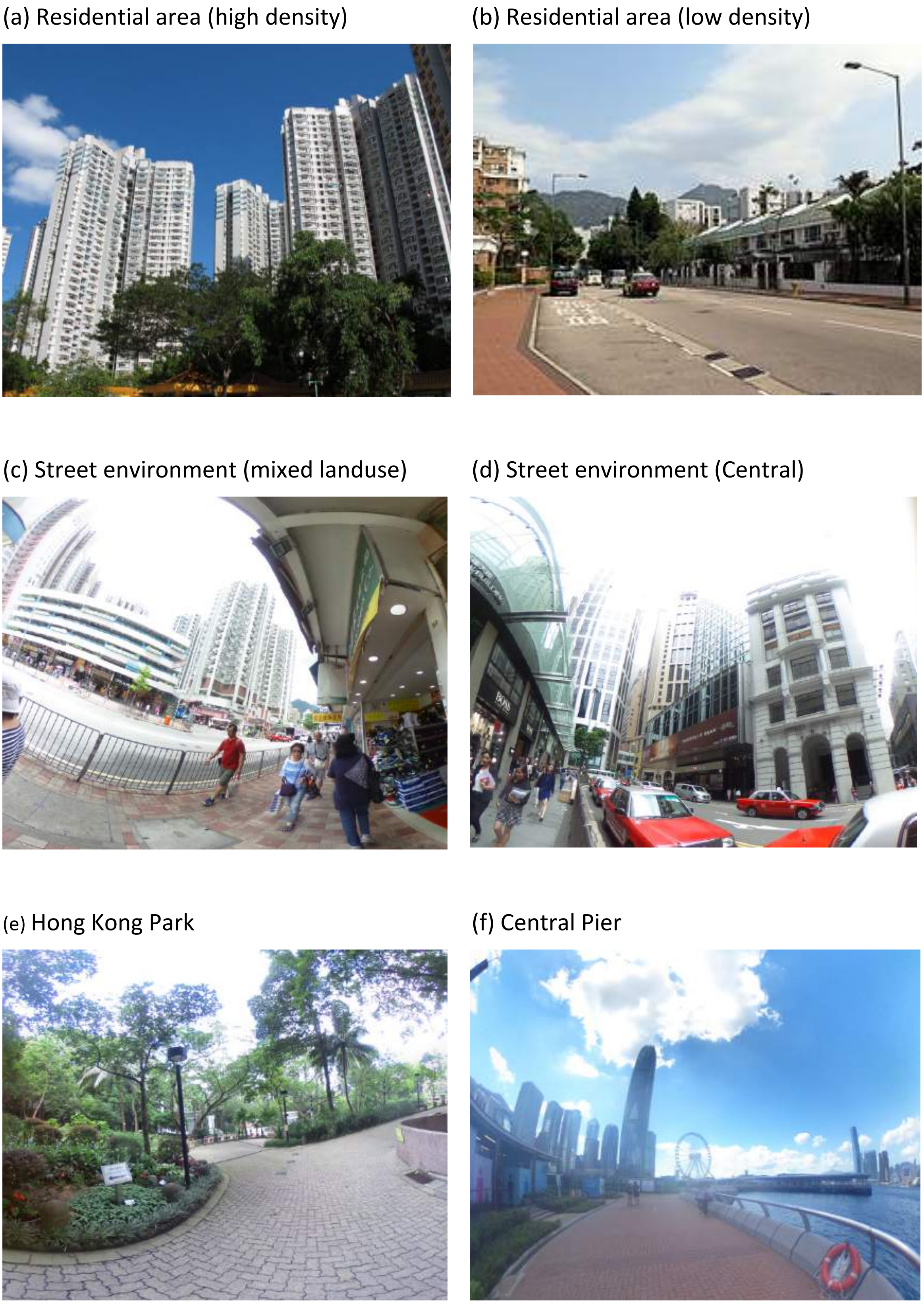


Figure 1 Examples of study sites showing the diverse urban environment in Hong Kong

2.2. Micrometeorological Measurement

Two mobile meteorological stations each containing a TESTO 480 data logger, a TESTO 480 Digital Microclimatic Sensor Set for measurements of air temperature (T_a, °C), relative humidity (RH, %) and wind speed (V_a, m/s) and a globe thermometer for measuring globe temperature (T_g, °C) (fig. 2). The globe thermometer is a TESTO flexible Teflon type K wire held inside a black painted table tennis ball with a diameter (D) of 38-mm and emissivity (ε) of 0.95. Mean radiant temperature (T_{mrt}) is determined by using measurements of globe temperature, air temperature and wind speed using the equation (Thorsson et al., 2007):

$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.335 \times 10^8 V_a^{0.71}}{\varepsilon D^{0.4}} (T_g - T_a) \right]^{1/4} - 273.15$$

The stations were placed very closely together and while one of the stations, with a sun shield attached to the humidity sensor, was placed under direct sunlight, the other (without shield) was placed under shade in a well-ventilated condition.

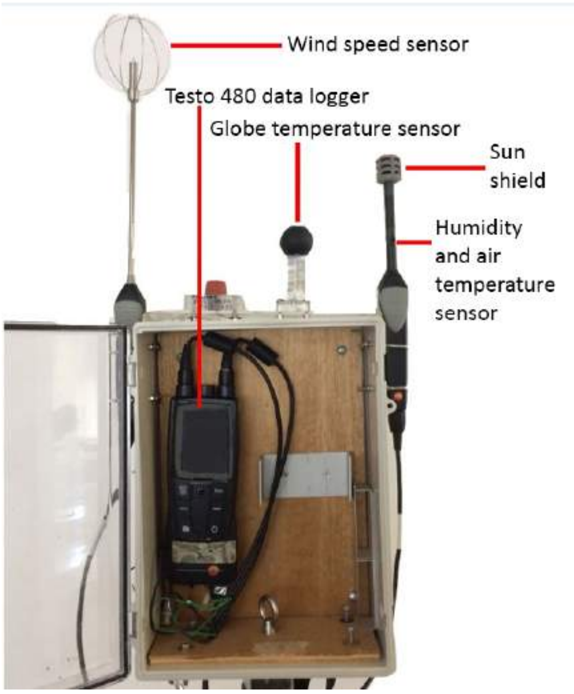


Figure 2 Set up of microclimatic measurement station

2.3. Questionnaire Survey

To collect the subjective outdoor thermal and environmental perception of outdoor space users in Hong Kong, a questionnaire survey (shown in figure 3) was utilized. The general public at the study sites during the survey sessions were invited to participate. Random sampling technique was used to reduce the effects of gender and age biases on survey results.

The questionnaire contains questions on the subjects' sensation to the thermal, wind, solar and humidity environments (using the 7-point ASHRAE scale) (e.g. thermal sensations were reported from "cold" (-3) to "hot" (3)), overall state of thermal comfort on a 4-point scale of "very uncomfortable" (-2), "uncomfortable" (-1), "comfortable" (1) and "very comfortable" (-2). In addition, the subjects' environmental perception was recorded on 5-point scales in terms of convenience (from -2: "very inconvenient" to 2: "very convenient"), visual comfort (from -2: "very unpleasant" to 2: "very pleasant"), acoustic comfort (from -2: "very noisy" to 2: "very quiet"), air quality (from -2: "very poor" to 2: "very good") and safety (from -2: “very unsafe” to 2: “very safe”). These qualities of outdoor space were chosen because, along with thermal comfort, they were suggested to be able to attract space users (Lai et al., 2014)

In addition to subjective thermal and environmental perception, demographic information such as gender and age were collected. Furthermore, the questionnaire recorded a number of observations made by interviewers including time and location of interview, whether the subject was under shade, and subject’s activity and clothing level using the activity and garment checklists from ASHRAE Standard 55 (2004).

2.4. Thermal indices

To account for the composite effect of metabolic activities, clothing and weather parameters (i.e. air temperature (Ta), mean radiant temperature (Tmrt), solar irradiation, wind speed (WS), relative humidity (RH)) on thermal perception, thermal indices such as the Physiologically Equivalent Temperature (PET) and Universal Effective temperature (UTCI) were developed (Coccolo, 2016). Conforming to the existing literature (e.g. Lin et al. 2010, Johansson and Emmanuel, 2006), PET, defined as the “air temperature at which the heat balance of the human body is maintained with core and skin temperature equal to those under the conditions being assessed” (Hoppe, 1999), was used in this study. PET was estimated on RayMan software by importing measured micrometeorological elements Ta, WS and RH), Tmrt (estimated using globe temperature (Tg), Ta, WS and diameter and emissivity of globe employed to measure globe temperature (Thorsson, 2003), and metabolic activity and clothing level recorded on questionnaire.

2.5. Statistical analysis

Since evaluation of thermal comfort were non parametric and not normally distributed, Kruskal-Wallis Test was applied to test the significance of the relationship between each environmental perception and thermal comfort and thermal sensation vote. As microclimatic factors also affect perceptions of thermal comfort and thermal sensation, ANOVA was performed to see whether PET, as an attribute that account for climatic and physiological elements, were statistically different across levels of environmental perception.

3. Results and Discussion

3.1. Outdoor climates

Microclimatic measurement campaigns in this study were conducted between 10:00 and 16:00 on 16 days between June and September 2017 in Hong Kong. Although the measurements were taken on different days, days of site visits were carefully chosen to ensure similar weather conditions were recorded. Recorded air temperature ranged from 29.6°C to 39.1°C and PET ranged from 29.1°C to 57.2°C. Mean Ta and PET were 33.8°C and 42.3°C respectively. It was previously found that mean PET in Hong Kong under shade in summer is between 32°C and 34°C and neutral PET for Hong Kong citizens is around 28°C in summer (Cheng et al., 2012). Our measurement results indicated the severity of heat stress in Hong Kong during its hot and humid summer in 2017. Under extreme heat stress, it was suggested that wind speed of more than 1.0 m/s would be necessary to ensure thermal comfort in outdoor spaces (Cheng et al., 2012). However, more than half of the recorded wind speed were below 1 m/s and less than 10% were above 1.5 m/s.

Table 1 Questionnaire used in this study

1. **Thermal sensation vote** 你覺得而家熱唔熱？

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
□$_{-3}$非常凍	□$_{-2}$幾凍	□$_{-1}$有少少凍	□$_{0}$啱啱好	□$_{1}$有少少熱	□$_{2}$幾熱	□$_{3}$非常熱

2. **Solar sensation vote** 你覺得而家太陽曬唔曬？

Very Weak	Weak	Slightly Weak	Neutral	Slightly Strong	Strong	Very Strong
□$_{-3}$非常唔夠	□$_{-2}$幾唔夠	□$_{-1}$有少少唔夠	□$_{0}$啱啱好	□$_{1}$有少少曬	□$_{2}$幾曬	□$_{3}$非常曬

3. **Wind sensation vote** 你覺得而家大唔大風？

Very Weak	Weak	Slightly Weak	Neutral	Slightly Strong	Strong	Very Strong
□$_{-3}$冇風	□$_{-2}$幾唔夠風	□$_{-1}$有少少唔夠風	□$_{0}$啱啱好	□$_{1}$有少少大風	□$_{2}$幾大風	□$_{3}$非常大風

4. **Humidity sensation vote** 你覺得而家空氣潮唔潮濕？

Very Dry	Dry	Slightly Dry	Neutral	Slightly Humid	Humid	Very Humid
□$_{-3}$非常乾燥	□$_{-2}$幾乾燥	□$_{-1}$有少少乾燥	□$_{0}$啱啱好	□$_{1}$有少少潮濕	□$_{2}$幾潮濕	□$_{3}$非常潮濕

5. **Thermal comfort** 總括嚟講，你覺得依個天氣舒唔舒服？

Very Uncomfortable	Uncomfortable	Comfortable	Very Comfortable
□$_{-2}$好唔舒服	□$_{-1}$唔舒服	□$_{1}$舒服	□$_{2}$好舒服

6. **Convenience perception** 你覺得依到方唔方便？

Very Inconvenient	Inconvenient	Neutral	Convenient	Very Convenient
□$_{-2}$非常唔方便	□$_{-1}$唔方便	□$_{0}$一般	□$_{1}$方便	□$_{2}$非常方便

7. **Visual comfort perception** 你覺得依到靚唔靚？

Very Unpleasant	Unpleasant	Neutral	Pleasant	Very Pleasant
□$_{-2}$非常唔靚	□$_{-1}$唔靚	□$_{0}$一般	□$_{1}$靚	□$_{2}$非常靚

8. **Acoustic comfort perception** 你覺得依到安唔安靜？

Very Noisy	Noisy	Neutral	Quiet	Very Quiet
□$_{-2}$非常唔安靜	□$_{-1}$唔安靜	□$_{0}$一般	□$_{1}$安靜	□$_{2}$非常安靜

9. **Air quality perception** 你覺得依到空氣好唔好？

Very Poor	Poor	Neutral	Good	Very Good
□$_{-2}$非常差	□$_{-1}$差	□$_{0}$一般	□$_{1}$好	□$_{2}$非常好

10. **Safety Perception** 你覺得依到安唔安全？

Very Unsafe	Unsafe	Neutral	Safe	Very Safe
□$_{-2}$非常唔安全	□$_{-1}$唔安全	□$_{0}$一般	□$_{1}$安全	□$_{2}$非常安全

3.2. Subjective thermal sensations and thermal comfort

Due to high air temperature during the survey campaign, most popular thermal sensation votes (TSV) were in the “hot” (+3) and “warm” (+2) categories with 38.7% and 33.2% of votes respectively. Only 28% of TSV were between -1 and 1, which is considered to be the comfortable range for thermal perception (Spagnolo and de Dear, 2003). Measured microclimatic parameters showed weak correlation with TSV and the Pearson correlation coefficients with air temperature and mean radiant temperature were 0.16 and 0.12 respectively. Although it further confirmed the previous findings that thermal sensation is mostly related to effects of air temperature and solar irradiance, our results suggest that the strong relationship between TSV and temperature, found in existing outdoor thermal comfort studies, deteriorate in extreme heat stress conditions (Nikolopoulou and Lykoudis, 2006).

Overall thermal comfort was also found to be weakly related to microclimatic parameters, and its correlation coefficients with air temperature, relative humidity, mean radiant temperature and wind speed were -0.150, 0.103, -0.05 and 0.002. This suggests that subjects tended to feel more comfortable in conditions with lower mean radiant temperature and air temperatures, while the impact of wind was very small. Thermal comfort is more significantly related to elements of climatic sensation such that the correlation coefficients with thermal, solar, wind and humidity sensation vote were -0.36, -0.23, 0.26 and -0.07. This suggests that the subjective evaluation of thermal comfort is most strongly related to thermal sensation, followed by wind and solar sensation. Although this might suggest that perception of the weather has a stronger influence on thermal comfort than the physical microclimatic environment itself, such correlation results cannot serve as evidence for causal relationships between variables.

3.3. Impacts of environmental perception on thermal sensation and thermal comfort

There are complex interrelationships between environmental perception and thermal sensation and comfort because positive evaluations of outdoor spaces can attract users and increase their tolerance to the thermal environment. On the other hand, thermal comfort as well as a physically thermal comfortable environment can lead to better perception of environmental qualities. However, it is important to understand the relationship between environmental perception and thermal perception in order to increase the range of thermal adaptation with appropriate urban design.

Based on Kruskal-Wallis Test, distributions of thermal comfort were significantly different across categories of convenience, visual comfort, acoustic comfort, air quality and safety at a significance level of 99% for all environmental variables. Similarly, distributions of TSV were different across categories of all investigated environmental parameters, with slightly lower significance levels of 95%. Results of ANOVA test between PET and environmental perceptions showed that PET did not vary significantly across levels of convenience ($P = 0.21$) and visual comfort ($P = 0.20$) perceptions, whereas they varied significantly ($P < 0.05$) across levels of acoustic comfort, air quality and safety.

The percentages of different TSV and thermal comfort votes in each category of environmental perception are shown in figure 3 and 4. Overall, the percentage of “comfortable” and “very comfortable” increased as environmental perception improved. While “-2” votes for each environmental parameter coincided with more than 80% votes being in the two hottest categories +2 (warm) and +3 (hot), the percentage of hot thermal sensation generally decreased as the perception of environment improved.

As the perception for convenience increased from -2 (very inconvenient) to 0 (neutral), the percentage of "hot" and "warm" TSV decreased from 83% to 70%. This decreasing trend reversed as perception of convenience improved from "neutral" to "very convenient". Contrastingly, the percentage of thermal comfort is lowest when convenience perception was neutral and there was a 10% increase in this percentage as convenience perception increased to +2 (very convenient). This suggests that although people tended to feel hot when they perceive the place as convenient, they also tended to be in a state of thermal comfort rather than discomfort. A possible explanation is that when a place is more convenient, or is perceived as so, it might be more connected to indoor spaces. This could mean that participants who voted for convenience level "1" or "2" either have shorter outdoor exposure time, or felt more thermally comfortable because of the ease of going to into air conditioned space.

The percentage of TSV 2 and 3 decreased steadily by 18% as the perception of visual comfort improved from -2 (very unpleasant) to 2 (very pleasant), while the percentage of thermal comfort votes increased by 36%. This indicates the large influence of visual comfort on reducing thermal sensation in extreme summer conditions and improving thermal comfort. It has been proposed that visual cues affect climate perception such that bluish and pale colors suggests coldness whereas warm colors indicate warmth (Vigier et al., 2015). Furthermore, it has been suggested that the presence of green and blue space can improve satisfaction with the visual environment as well as thermal comfort (Klemm et al., 2015). However, where green and blue space is present, wind speed may also be higher. Further studies are required to find out how much of the improvement in thermal comfort was purely due to the psychological processes of improving visual perception rather than changes in the physical environment.

As the perception of acoustic comfort improved from -2 (very noisy) to 2 (very quiet), the percentage of TSV 2 and 3 decreased by 12%. Meanwhile, the percentage of thermal comfort votes increased by 25%. Similarly to visual comfort perception, people significantly generally felt less warm and more thermally comfortable when they are more satisfied with the acoustic environment. The perception of noise might have indicated the presence of more people and cars, which can generate negative feeling of crowdedness and lead to warm sensation and thermal discomfort.

The percentage of 'hot' and 'warm' TSV decreased by 25% while percentage of thermal comfortable vote increased by 45% as perception of air quality increased from "very poor" to "very good". This indicates a striking improvement in thermal perception as the perception of air quality improved. Poorly ventilated places surrounded by high rise buildings with lower wind speed and higher air temperature might cause the perception of poor air quality, whereas open space with higher wind speed could result in the perception of good air quality. Moreover, By the same token as acoustic comfort, the perception of poor air quality might suggest crowdedness and therefore lead to warm sensation.

The percentage of thermal comfort votes increased by 24% as safety perception improved from -2 (very unsafe) to 2 (very safe), which indicates that thermal comfort improve significantly with safety perception. While all participants who voted for "-2" in terms of safety perception also voted for the two hottest TSV categories, the percentage of TSV 2 and 3 fluctuated between 69% to 75% in other safety perception categories. This suggests that unless a place is perceived as very unsafe, the perception of safety does not affect thermal comfort significantly.

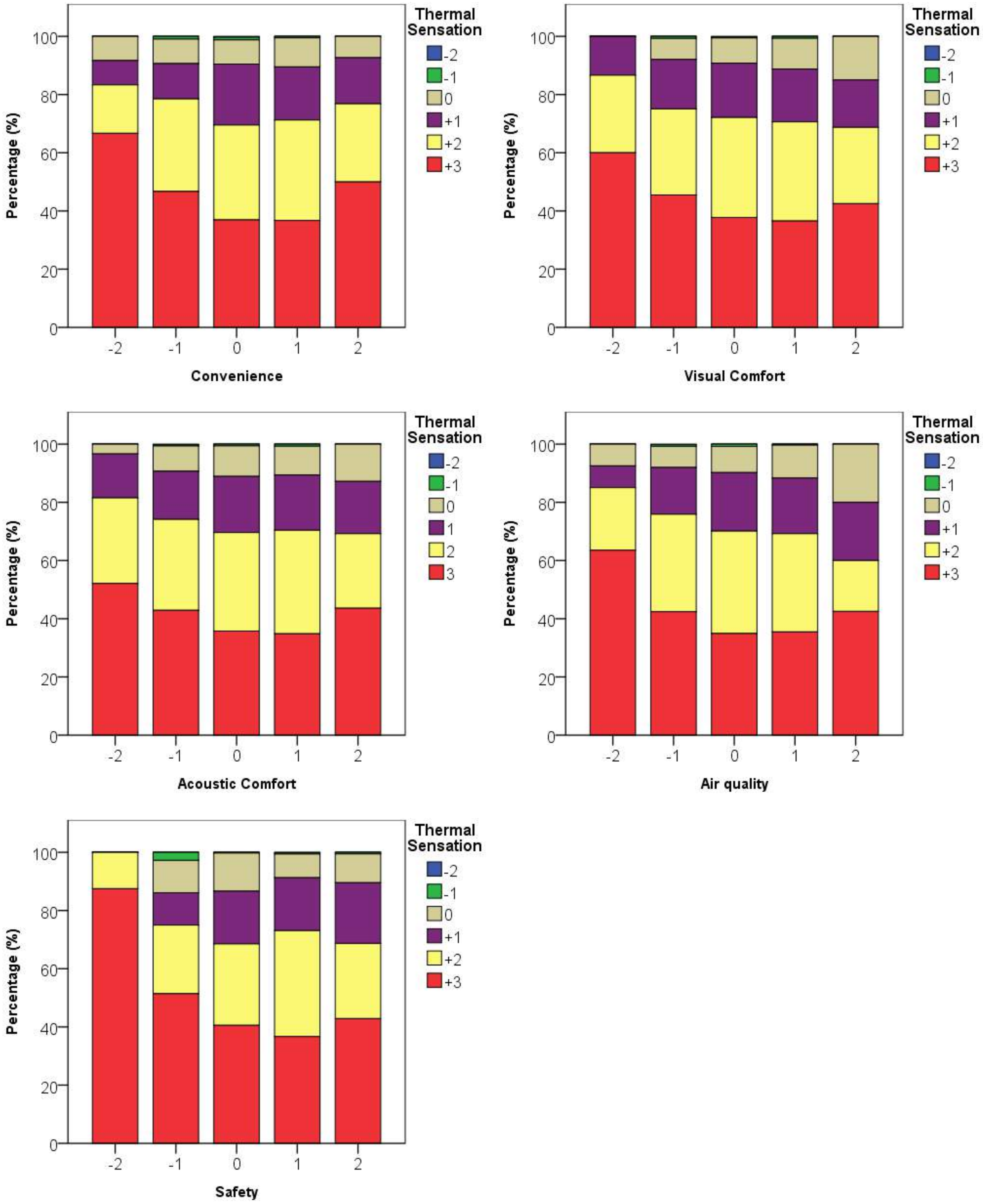


Figure 3 Percentage of thermal sensation votes as a function of environmental perception levels

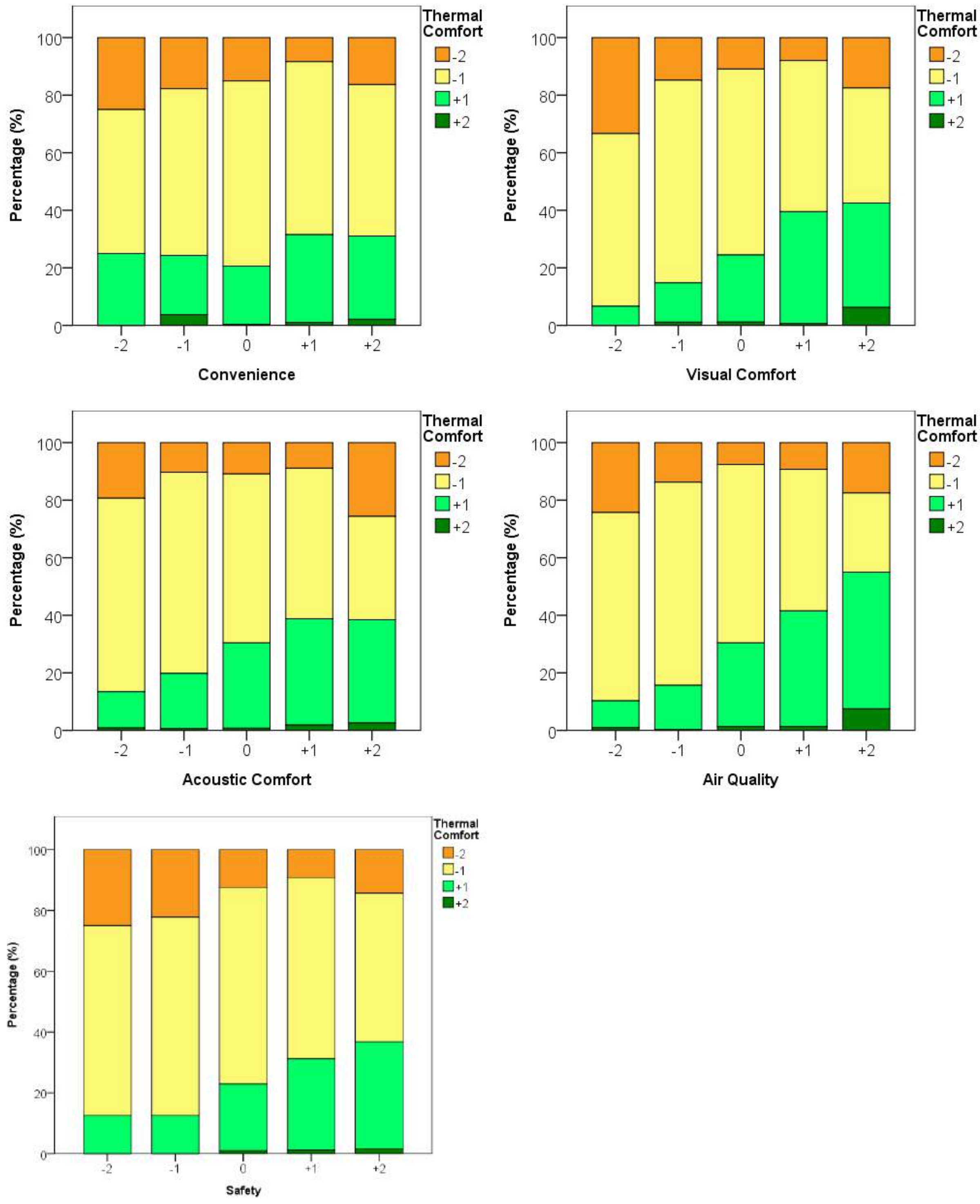


Figure 4 Percentage of thermal comfort votes as a function of environmental perception levels

4. Urban planning implications

In correspondences to the existing literature (e.g. Lin et al., 2013), correlation analysis in this study suggests the high importance of air temperature and mean radiant temperature in affecting thermal comfort. It is particularly important to provide shading facilities in urban outdoor spaces during extreme heat stress in the subtropics.

Additionally, our results show that perceptions of the environment are of significant importance to thermal comfort. Although previous studies have identified links between thermal comfort and the visual and acoustic environment, these studies usually focused on the presence and absence of few specific visual and acoustic cues such as green areas, water features, high/low rise buildings. A different approach is proposed in this study where the relationship between thermal comfort and the degree of positive feeling towards aspects of environmental perception are evaluated. It is shown that thermal comfort increases with all investigated qualities of an outdoor environment. The increase in percentage of thermally comfortable votes (+1 and +2) was substantial for air quality, acoustic comfort and visual comfort. While improvements in city scale planning is required to improve outdoor air quality within parts of Hong Kong, local scale planning strategies should attempt to increase overall visual and acoustic comfort as they have considerable ability to increase thermal tolerance.

Despite the significant impacts of various environmental perception on thermal perception and comfort in this study, further studies are required to separate the impact of microclimatic environments from psychological effects on thermal tolerance. Furthermore, investigations of factors that influence the evaluation of environmental perception should be conducted in order to identify specific causes for the increase in thermal tolerance by psychological adaptation.

5. References

Cheng, V., Ng, E., Chan, C., Givoni, B., 2012. Outdoor thermal comfort study in a sub-tropical climate: a longitudinal study based in Hong Kong. Int J Biometeorol 56, 43–56.

Coccolo, S., Kämpf, J., Scartezzini, J.-L., Pearlmutter, D., 2016. Outdoor human comfort and thermal stress: A comprehensive review on models and standards. Urban Climate 18, 33–57.

Hirashima, S.Q. da S., Assis, E.S. de, Nikolopoulou, M., 2016. Daytime thermal comfort in urban spaces: A field study in Brazil. Building and Environment 107, 245–253.

Höppe, P., 1999. The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. Int J Biometeorol 43, 71–75.

Johansson, E., Emmanuel, R., 2006. The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka. Int J Biometeorol 51, 119–133.

Johansson, E., Thorsson, S., Emmanuel, R., Krüger, E., 2014. Instruments and methods in outdoor thermal comfort studies – The need for standardization. Urban Climate, ICUC8: The 8th International Conference on Urban Climate and the 10th Symposium on the Urban Environment 10, 346–366.

Klemm, W., Heusinkveld, B.G., Lenzholzer, S., Jacobs, M.H., Van Hove, B., 2015. Psychological and physical impact of urban green spaces on outdoor thermal comfort during summertime in The Netherlands. Building and Environment, Special Issue: Climate adaptation in cities 83, 120–128.

Lai, D., Zhou, C., Huang, J., Jiang, Y., Long, Z., Chen, Q., 2014. Outdoor space quality: A field study in an urban residential community in central China. Energy and Buildings, The 2nd International Conference on Building Energy and Environment (COBEE), 2012, University of Colorado at Boulder, USA 68, 713–720.

Lin, T.-P., de Dear, R., Hwang, R.-L., 2011. Effect of thermal adaptation on seasonal outdoor thermal comfort. Int. J. Climatol. 31, 302–312.

Lin, T.-P., Matzarakis, A., Hwang, R.-L., 2010. Shading effect on long-term outdoor thermal comfort. Building and Environment, International Symposium on the Interaction between Human and Building Environment Special Issue Section 45, 213–221.

Lin, T.-P., Tsai, K.-T., Liao, C.-C., Huang, Y.-C., 2013. Effects of thermal comfort and adaptation on park attendance regarding different shading levels and activity types. Building and Environment 59, 599–611.

Nikolopoulou, M., Lykoudis, S., 2006. Thermal comfort in outdoor urban spaces: Analysis across different European countries. Building and Environment 41, 1455–1470.
Nikolopoulou, M., Steemers, K., 2003. Thermal comfort and psychological adaptation as a guide for designing urban spaces. Energy and Buildings, Special issue on urban research 35, 95–101.
Spagnolo, J., de Dear, R., 2003. A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. Building and Environment 38, 721–738.
Thorsson, S., Lindberg, F., Eliasson, I., Holmer, B., 2007. Different methods for estimating the mean radiant temperature in an outdoor urban setting. Int. J. Climatol. 27, 1983–1993.
Vigier, T., Moreau, G., Siret, D., 2015. From visual cues to climate perception in virtual urban environments, in: 2015 IEEE Virtual Reality (VR). Presented at the 2015 IEEE Virtual Reality (VR), pp. 305–306.
Yang, W., Wong, N.H., Jusuf, S.K., 2013. Thermal comfort in outdoor urban spaces in Singapore. Building and Environment 59, 426–435

Acknowledgement

This study is supported by Direct Grant for Research, The Chinese University of Hong Kong (Grant no.: 4052157) and Research Grants Council, Hong Kong (RGC Ref No. 14603617)

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Thermal Environments and Comfort Perception in Shophouse Dwellings of Ho Chi Minh City

Hung Thanh Dang [1] and Adrian Pitts[1]

[1] Centre for Urban Design, Architecture and Sustainability; University of Huddersfield, Huddersfield; Thanh.Dang@hud.ac.uk and A.Pitts@hud.ac.uk

Abstract: This paper reports on a long-term investigation into the thermal environment and perceptions of comfort in dwellings located in Ho Chi Minh City. Of particular interest is the so-called 'shophouse' dwelling types prevalent in Vietnam and other SE Asian countries. Shophouses are narrow urban buildings used for business as well as living accommodation. A review of shophouses across the city determined three main types (traditional/new/row house) and four subgroups. Automated data recording systems were set up for longitudinal investigations (long-term recording of air temperature/humidity/movement) in four dwellings coupled with occupant questionnaires/interviews and shorter cross-sectional studies in additional buildings. The paper explains the techniques utilized to derive optimum data collection and some of the difficulties encountered. Summaries of the extensive data are presented noting for the warm season, typical indoor temperatures ranged from 29-35°C though the neutral temperature was 28.5°C (upper limit to the comfort range =31.5°C). The results are compared to previous comfort research findings. Due to the nature of the dwellings, an important environmental factor was considered to be air movement. Though there was a correlation between internal/external airspeed, indoor air movement rarely exceeded 0.2ms^{-1}. Design guidelines/suggestions for optimising comfort are made based on shophouse type.

Keywords: shophouses, thermal environment, perceptions, comfortable temperature, thermal preference.

1. Introduction

Most dwellings constructed in Vietnam use natural or mixed-mode ventilated mechanisms to support comfort for building occupants. Thus, the influences of the regional tropical climate along with climate change and urban heat island (UHI) impacts have exacerbated thermal discomfort. This is also linked to additional, perhaps excessive energy use for mechanical cooling systems in residential buildings during summer months, particularly in shophouse type dwellings. According to energy statistics in Vietnam, the energy consumption in households has taken an increasing and significant proportion of total energy use over the last decade and more: it was 22.4% in 2003; 31% in 2010; and 38% in 2014 (Duc, 2016). In addition, results of investigations of energy use in dwellings across the country by the Cimigo market research group show that householders living in shophouses used 69% of the total energy provision for all three housing types found in Vietnam: shophouse; villa; and apartment (Parkes, 2013). This marks the shophouse dwellings as a very important component of energy demand in Vietnam.

A review of international thermal comfort standards such as ASHRAE standard 55 and ISO7730, the comfort temperature and comfort zone for occupants indicated a lower value than studies of tolerance and adaptation in the tropics would suggest. This conclusion is supported by field studies of several researchers in SE Asia (Karyono, 2000) (Feriadi & Wong, 2004) (Djamila, et al., 2013). In this paper, the authors suggest that some review and revision can be carried out; they believe that the shortcomings of certain standards may be attributed to the modest number of thermal comfort studies conducted in naturally ventilated (NV) buildings in the tropical regions.

Although the number of attempts to study thermal comfort in equatorial climates has developed and expanded since 1950, research work in residential buildings has been somewhat limited. This could be responsible for a deviation in evaluation and conclusion of comfortable conditions for the occupants in warm climates (Djamila, et al., 2012). In addition, the national standards for the conditions of thermal comfort being implemented in Vietnam such as TXCDVN 306:2004 and TCVN 7438:2004 have been adopted and adapted from international standards. This also shows a lack of supporting evidence from empirical surveys and experiments in real-world local environments. Therefore, the authors here suggest that they do not fully reflect comfortable conditions and thermal perceptions of the Vietnamese.

The gaps in research of comfort set against balancing available energy supplies with demand for use for dwellings in Vietnam, especially shophouses, provided the motivation for the research reported in this paper. As a result of a comprehensive field survey including cross-sectional/longitudinal methods and occupant responses, this has been carried out for 'free-running' shophouse buildings in Ho Chi Minh City (HCMC). The specific focus of this paper is on the data from the cross-sectional studies, which has been analyzed to provide a better understanding of shophouse environments linked to the architecture across the city; and also the experience of the local people living in the warm conditions. The objectives of this study are to examine environmental performance in/around the buildings and to investigate comfort perception and preference expressed by the residents of naturally ventilated and hybrid conditioned shophouses in HCMC.

2. Climatic conditions in HCMC

HCMC (formerly Saigon) is the second largest city in the country and is located in the south-central part of Vietnam. The city is characterized by a tropical monsoon climate with the key features of high air temperature and high humidity across much of the year.

The average monthly maximum temperature and humidity lies between 31-35°C and 69-92% (IBST, 2009). There are two dominant monsoon seasons: south and southeast monsoon winds in dry months with a maximum airspeed of $4.5ms^{-1}$; the west and southwest monsoon winds in the rainy months with the strongest wind reaching $5ms^{-1}$. The urban expansion of the city, as well as the increasing ambient temperatures arising from global warming, are accelerating the vulnerability of the urban climate. The city's mean temperature has risen by 0.9-1.2°C since 1958; moreover, the extreme temperatures in summer can peak at 40°C, and an increase of 20% rainfall in the rainy season has been experienced (Thuc, et al., 2016). The climate changes and man-made modification result in unsatisfactory microclimatic conditions in and around buildings, and trends of increasing energy use by households to reduce discomfort.

3. 'Shophouse' dwellings in HCMC

In essence, the 'shophouse' dwellings in Vietnam are terraced houses; however, the features of vernacular culture, society, history, and architecture are catalysts that have formed this unique housing type, although variations are also found in other regions of SE Asia. It is a combination of both 'shop' for commercial/retail/work purposes normally found on the ground floor, and 'house' providing accommodation on the upper floors. An overarching view of the morphologies of shophouses shows they are diverse in size, configuration, style, and structure. However, having a long and narrow shape as a ‘tube’ is a principal characteristic of these dwellings.

Figure 1. Five shophouse types found in HCMC

Shophouses have typical dimensions ranging from 3-5m in width, 10-100m in length, and 1-5 floors in height; when originally planned/built (1850 onwards) they provided scope for use of natural daylight and ventilation. However, since the mid-20th century, pressures on urban space have led to significant changes. The studies in 2010 determined 20.1% of land in HCMC was completely covered by buildings, reducing natural light and ventilation options (Downes, et al., 2011). This, combined with urban heat island effects now, causes significant difficulties for the internal environments of shophouses. Energy availability issues and its cost means conditions in shophouses can reach and exceed the upper limits of acceptability and choices have to be made between energy-use and comfort.

Arising from a survey of land use conducted in HCMC between 2009 and 2014, a total of five shophouse typologies were identified: rudimentary (type 1), traditional (type 2), new (type 3), commercial (type 4), and row house (type 5) (Moon, et al., 2009). Examples of each type are shown in figure 1. The housing types 3 and 5 are the most dominant; type 2 buildings generally constructed between the 1850s and 1920s are special types found in certain places around the city. Figures 2 and 3 depict the most popular spatial layout of floor plans of a new shophouse in HCMC with the ground floor left for use as a shop. All family members live on the upper floors. The main spaces such as bedrooms and living room are organized close to the façade to allow penetration of natural light and air flow. The service rooms are located at the rear. The staircase is normally positioned in the middle as the main element not only to connect all the different spaces of a house but also to allow deeper access for daylight and natural ventilation through the house. On the top floor, the householders usually arrange a worship room, a small garden at the front, and a drying court at the back.

4. Research methods

A total of 59 households with 117 individual respondents were involved in a field study which took place in HCMC in the warm months of 2017. A summary of samples is listed and classified by shophouse type in Table 1. As previously mentioned, research was carried out to investigate comfort conditions of three main dwelling typologies: traditional house, new shophouse, and row house; these are selected because of their predominance in the city. The cooling mechanism used in most cases is a hybrid type with air-conditioners being operated at certain times of the day/month/year; just 3 of the houses were entirely cooled by natural ventilation. Room fans were also usually employed to provide air movement cooling.

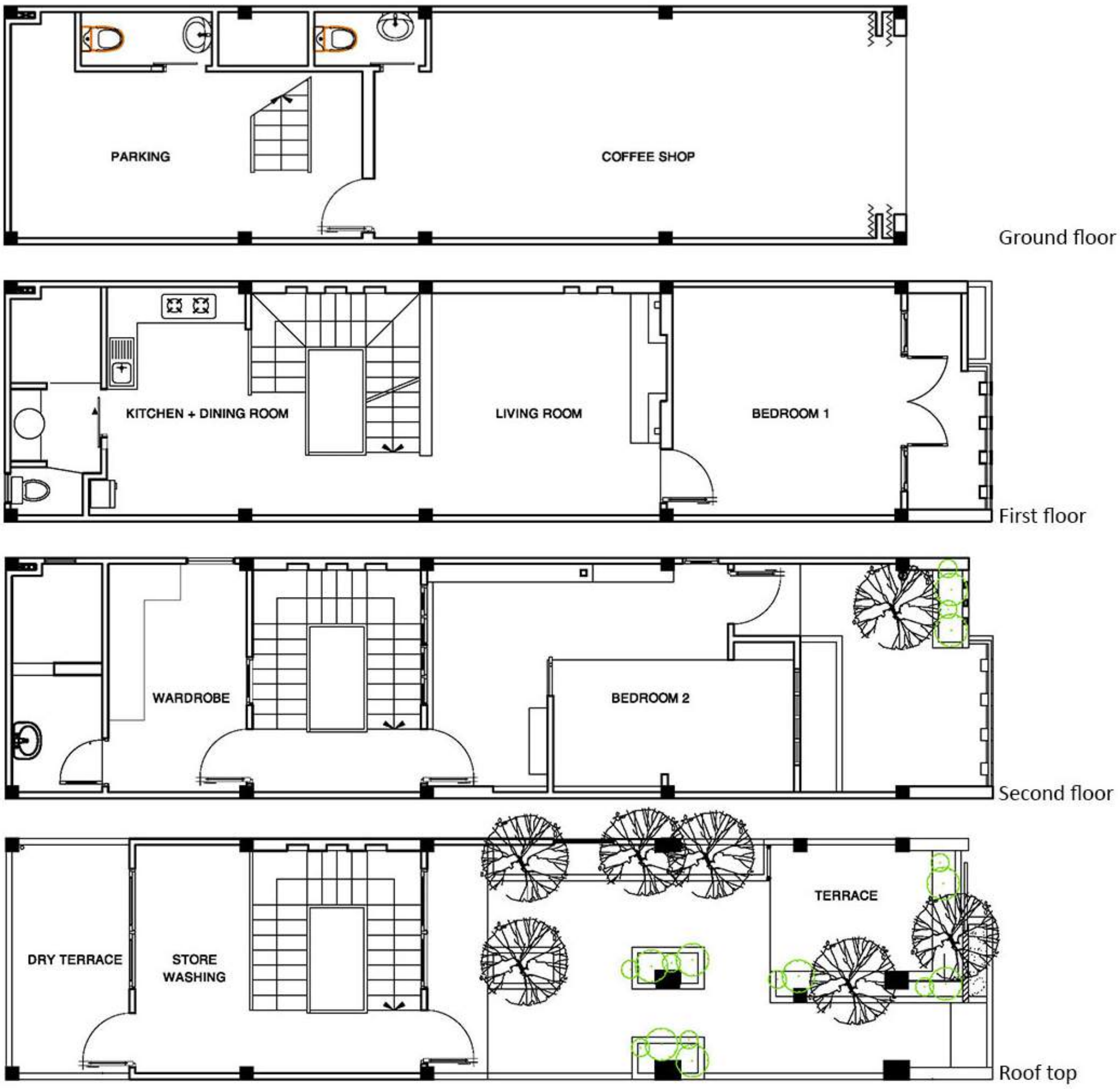


Figure 2. An example of a new shophouse in HCMC – No 6, Street No 41, District 4

Figure 3. Indoor environment of a shophouse at No 6, Street No 41, District 4

There were two survey types used for the field work including investigations of indoor and outdoor physical environment of buildings; and thermal comfort survey using questionnaires. All surveys were conducted in the natural conditions of the environment. It means that the options for mechanical ventilation were switched off. For the study of environmental conditions, both techniques of cross-sectional measurements and longitudinal recording were used. The variables of air temperature, humidity level, air velocity, and light level were measured room by room; the positions for measurement of wind flow and daylight were selected following 3D and 2D rectangular systems respectively. The instruments employed in the studies were tested and calibrated before use and were selected to give an optimum combination of reliability, accuracy and cost. Each spot measurement was made every 30 seconds. A total of 4 houses from 16 initially selected from the cross-sectional surveys were chosen for the installation of a more complete the data logging system which was responsible for recording the physical factors in and around the buildings for ten months.

Table 1. Sampling distribution

Type	No of houses	No of subjects
Traditional house	3	3
New shophouse	46	22
Row house	10	92
	59	**117**

For thermal comfort surveys, the questionnaires about sensation, acceptability, and preference of subjects to the thermal environment were administered for completion by the subjects. Meanwhile, at the same time measurements of the thermal environment were made. The occupants selected were chosen because they spent a minimum of 6 hours per day at home.

In previous field studies, the subjects were usually arranged in the same room for survey questioning and logging of measurements. However, in reality, spatial use of the dwelling means that people's daily activities are very flexibly located around their house. Therefore, obtaining responses of subjects should be carried out in different rooms where they are more naturally located instead of in the same room; this was the approach taken in this survey.

Before responding to the survey form, all participants were provided with briefing notes to explain the purpose and procedures. Each survey took about 15 minutes to fill in. The scales of ASHRAE Standard 2004 and McIntyre were applied; however, they were modified according to the condition of warm climate. The meters were located within a radius of 1m around the subjects. Depending on people’ posture such as sedentary activity, standing or lying, the environmental data were collected at different heights – 0.1m, 0.6m, 1.1m, and 1.7m above the floor. The time to read values was 30 seconds after activation of the meter.

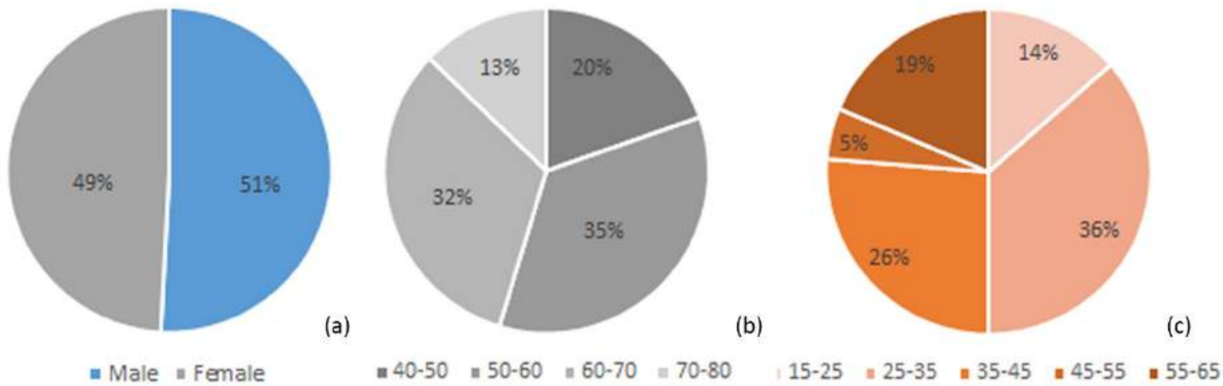


Figure 4. Summaries of personal parameters (a: gender, b: age, and c: weight (kg))

Respondents' parameters are shown in Figure 4 including gender, age, and weight. The range of their ages is between 15 and 65, and the health was self-reported as good for those chosen for the study. Most of them are in the age bands of 25-35 (26%) and 35-45 (36%). The ratio of male and female shares the same proportion. Furthermore, the major weights of the Vietnamese are in the ranges of 50-60kg (35%) and 60-70kg (32%).

5. Analysis and results of field study

5.1. Indoor and outdoor climate

The statistical summary of the 117 sets of records of climatic conditions in and around the buildings, whilst the occupants were being surveyed, is described in Table 2. Handheld instruments were used for measurements in occupied zones of the buildings. All indoor values were averagely calculated based on the measurements at three height levels above the floor while the outdoor parameters of temperature and humidity were recorded simultaneously at a single consistent height outside the building. The external airspeeds were also measured at three various heights in front of the buildings, and then generating the average numbers.

The indoor and outdoor air temperatures show the typically warm condition of the environment during summer months. The maximum inside and outside air temperature peaked at 34.6°C and 37.8°C respectively. The mean values of indoor air temperature (T_a), mean radiant temperature (MRT), and Operative Temperature (T_{op}) were similarly at 32°C. However, whilst the minimum temperature of the three variables was very alike, the maximum level of MRT was 1°C higher than the others. The standard deviation of three temperatures was almost the same. The hot conditions found in the indoor environment probably results from high solar loads, the low thermal mass, and weak natural ventilation in the shophouse dwellings in HCMC. The indoor operative temperature had a mean of 31.5°C and a maximum of 34.8°C (Figure 5).

Table 2. Summary of the indoor and outdoor climate

	Indoor				Outdoor			
	Mean	SD	Max.	Min.	Mean	SD	Max.	Min.
Air temperature (°C)	31.9	1.18	34.6	29.1	32.8	1.74	37.8	29.5
Relative humidity (%)	61.9	7.29	76.9	44.9	59.5	8.30	79	41
Mean radiant temperature (°C)	32.0	1.35	35.5	29.0				
Operative temperature (°C)	31.9	1.24	34.8	29.1				
Air velocity (ms^{-1})	0.14	0.10	0.55	0.01	0.32	0.22	1.0	0.07

Relative humidities indoors were not excessively high on hot days, with a mean of 61.9%, maximum of 76.9%, and a minimum of 44.9%. The outdoor environment had a mean humidity level of 59.5%. Air velocities were relatively low in the naturally cooled buildings, with a mean of 0.14ms^{-1}. In some cases, a more pleasant condition of air movement, in the range of 0.25 – 0.55ms^{-1}, was measured in spite of some very low flow external wind environments. The mean and maximum outdoor wind speeds were recorded at 0.32ms^{-1} and 1.0ms^{-1} respectively. During observations of the thermal condition in shophouses in HCMC, the occupants made use of different kinds of fans to create air movement including wall mounted, free-standing, and ceiling fans.

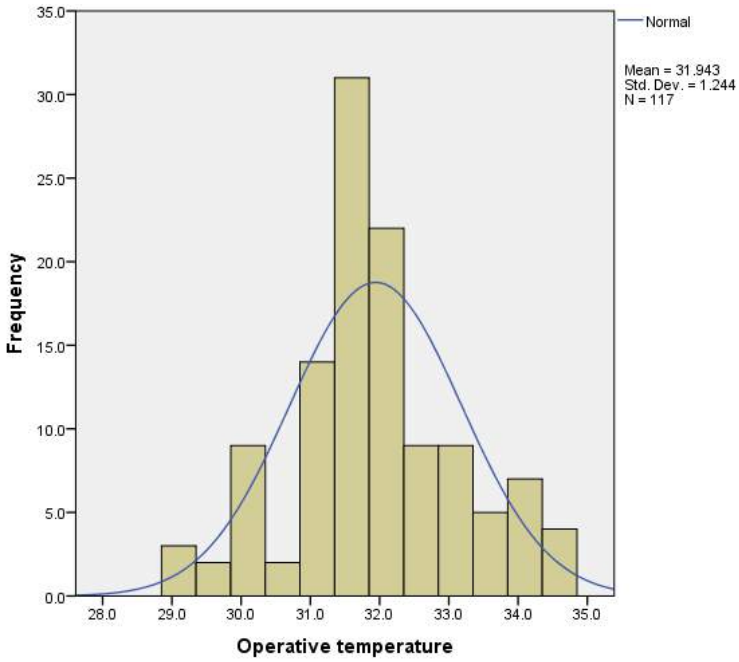


Figure 5. Distribution of operative temperature

5.2. Thermal comfort responses

In order to collect thermal responses of the subjects, the standard scales and questionnaires for the survey were translated into the Vietnamese language. All 117 subjects were asked for their thermal sensation to a seven-point ASHRAE scale (+3 – hot, +2 – warm, +1 – slightly warm, 0 – neutral, -1 – slightly cool, -2 – cool, and -3 – cold) under warm climate condition. Figure 6(a) indicates the highest percentage of thermal sensation votes (TSV) of approximate 50% occurred at +2 (warm). 45% of the subject votes fell into an acceptable range from -1 (slightly cool) to +1 (slightly warm) according to ASHRAE Standard 55, 2004, in which, 25% occupants felt comfortable at a mean operative temperature of 31.5°C. It is observed that 5% of people responded as having a too hot sensation at temperatures of 33 - 34°C – see Figure 6(b).

The linear regression analysis between two variables - indoor operative temperature and subjective vote found a quite strong relationship:

$TSV = 0.36\, T_{op} – 10.23$ (1)

($R = 0.398$, $R^2 = 0.159$, Sig. =0.000, BCa 95% CI = [0.190, 0.519])

The neutral temperature was 28.5°C and the upper limit of comfort range in warm months was 31.5°C. The statistical value of R squared (0.398) is explained by the strong link to indoor operative temperature for the occupants' responses. In hot humid climates such as frequently occur in HCMC, people appear to tolerate a warmer condition than others at high and medium altitudes. The long-term acclimatisation and flexible behavioural adjustments of people to regional climate could provide a reason for the level of acceptability. And perhaps, these explain why subjects sensed neutral in spite of the observed temperatures of over 31.5°C.

Although the zone of acceptable temperatures for the naturally ventilated residences in warm months lies between approximately 28.5°C and 31.5°C, the environmental condition indoors cannot be considered as offering true thermal comfort. Approximate 65% observed data show indoor operative temperatures higher than the upper limit of the comfort zone.

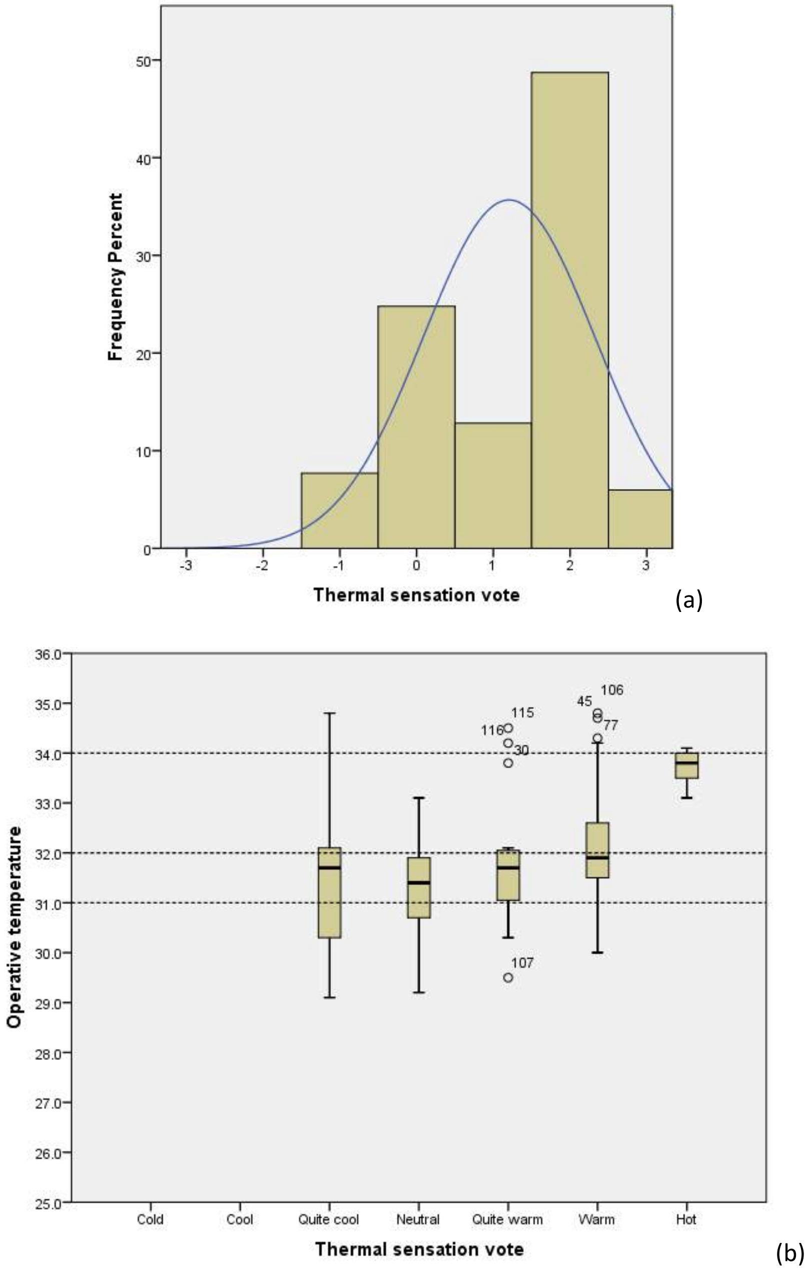


Figure 6. Distribution of thermal sensation votes
(frequency of subjective responses – a, and relationship to operative temperature - b)

5.3. Comparison with predicted mean vote (PMV) model

Another histogram analysis of predicted comfort was carried out by computing the values of PMV results using the Center of the Built Environment (CBE) Berkeley, Thermal Comfort Tool. For comparison between the distribution of TSV and PMV, it should be noted that almost all calculations related to warm conditions lie outside of the acceptable thermal environment for comfort (-0.5<PMV<0.5) with 10% PPD (predicted percentage of dissatisfied). However, if predicted mean votes are normalised into a seven-point scale of TSV (-0.5 < PMV < 0.5 set as 0/neutral, 0.5 < PMV < 1.5 set as +1/slightly warm) etc, 80% of the results produced by the heat balance model are in "warmer than neutral" region (> +1) see Figure 8. There seems to be a discrepancy between the predicted votes and what might be otherwise expected from subjects located in a hot tropical climate.

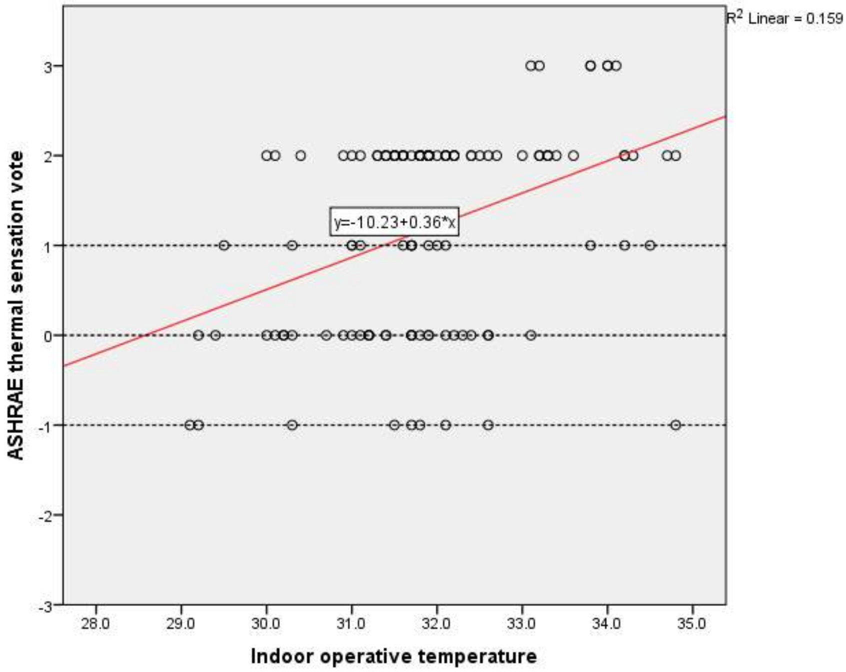


Figure 7. Linear regression of indoor operative temperature and ASHRAE sensation votes

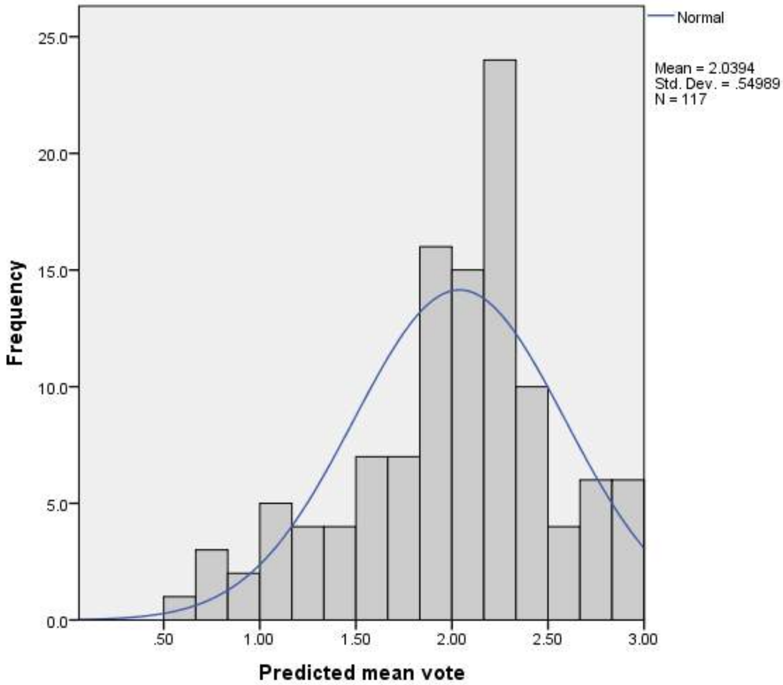
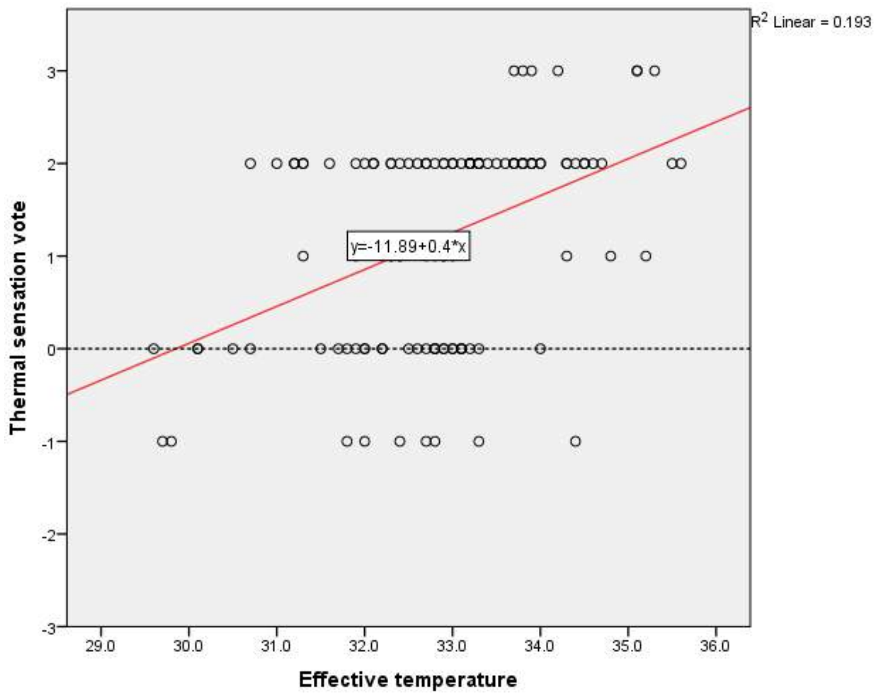


Figure 8. Correlation of operative temperature and PMV

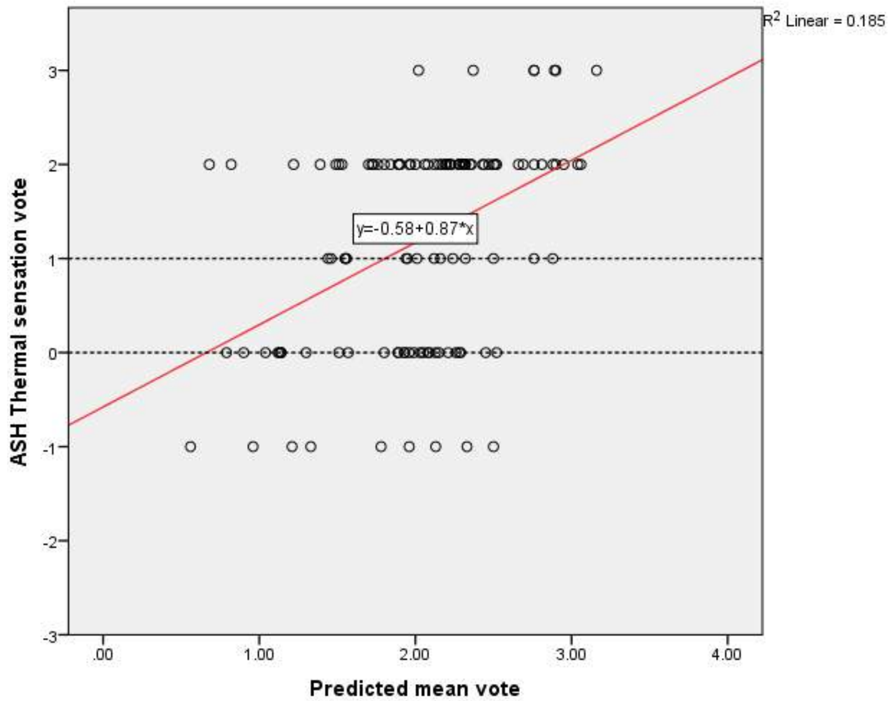
Figure 9 introduces two linear regressions defined between the dependent variable (TSV) and independent variables as follows: effective temperature (a) and predicted mean votes (b). The correlation coefficient of both regressions shows the large effect of two variables: Ra = 0.440 and Rb = 0.430. In Figure 9(a), the intersection of the linear model and reference line at value 0 of TSV identifies the neutral temperature at 29.7°C Effective temperature (ET). This output is 1.2°C warmer than the comfort temperature estimated by T_{op}. The model generated from the linear analysis of TSV and ET is:

TSV = 0.4 ET – 11.89 (2)

In comparison between two equations (1) and (2), the difference between respective regression gradients and intercepts is significant.



(a)



(b)

Figure 9. Correlation of effective temperature (a) and PMV (b) and thermal sensation votes

In Figure 9(b), over 90% of plots on the scatter chart are located in the warmer region; PMV > 1. The outputs of statistical analysis (R = 0.430, R square = 0.185, Sig. = 0.000, BCa 95% CI = [.524, 1.206]) illustrate an imbalance between using the two variables. In other words, the model of Fanger fails to predict the comfort temperature for the occupants. The equation indicates that when TSV is equal to 0 and +1, PMV has values of +0.7 and +1.8 respectively.

In the lower part of the chart (at the level of -1), the significant deviation in comfort prediction between two models can also be seen. Some subjects indicated that they felt slightly cool in the recorded observations; however, the prediction of the Fanger model indicates outcomes from ‘slightly warm’ to the ‘hot’ condition.

5.4. Thermal preference

The thermal preference votes utilised a seven-point scale (3 - hotter, 2 - warmer, 1 - little warmer, 0- no change, -1 - a little cooler, -2 - cooler, and -3 – colder) corresponding to thermal sensation scale to identify the preferred temperature of the subjects. The asymmetrical result showed over 95% occupants preferred a cooler condition during the summer season. Most of them voted for preferences of (little cooler) and (cooler) – see Figure 10. The number of these votes was approximately equivalent to the number of subjects who felt warm and hot under observed environmental condition.

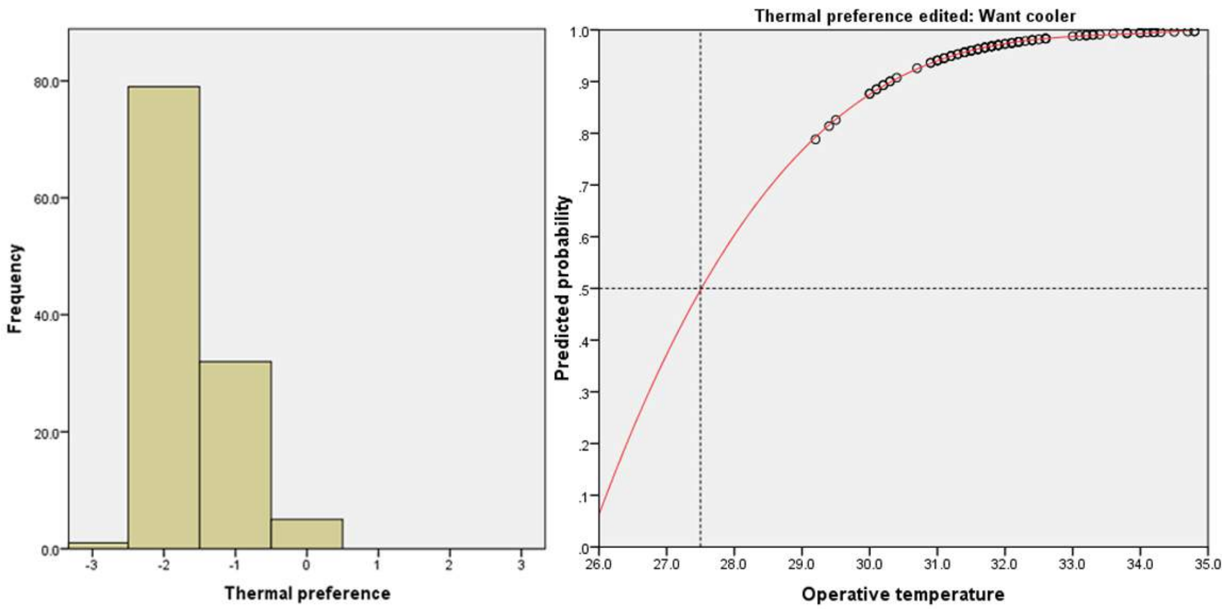


Figure 10. Analysis of thermal preference

A binary logistic analysis was run separately for the two groups of preference votes - “want to be cooler” (<0) and “no change” (=0). The preferred temperature was determined at the intersection of the regression and reference line at the probability of 50% as a neutral percentage of people who want to be cooler. Although the real data do not show completely on the lower part of the exponential line, outputs after analysing are significant in statistical terms (R square = 0.999, Sig. of Chi-square = 0.013, Wald statistic = 3.741 and its Sig. = 0.05, and Exp (B) = 2.243). The logistic analysis between preference vote of “want to be cooler” and operative temperature shows the subjects desire the cooler condition rather than the neutral temperature found. The preferred temperature is 27.5°C, which is 1°C lower than comfort temperature. In reality, the desirable environment for people is not easy to achieve in a real environment in Vietnam as the present, where the internal ambient temperatures experienced during the survey were much higher than what might be predicted as desirable.

5.5. Comparison with previous findings

The first comparison was carried out between the work described in this paper and previous studies on thermal comfort by researchers in Vietnam. Two research project reports found had examined the occupants' responses to their immediate environment but using different approaches. These were an experimental study of 40 respondents in an air controlled chamber built in Hanoi (Nguyen, et al., 2003) and field study which collected 1200 subjective responses in the University of Danang during summer months (Nguyen, 2013). It is possible that the neutral operative and effective temperatures defined by Nguyen in 2012 and in the study reported in this paper in 2017 are consistent with the comfort range found by Nguyen, et al. in 2003. However, in the comparison between the empirical study conducted in 2012 and this paper's findings from studies undertaken in 2017, the occupants of dwellings were found to have a neutral thermal sensation at 28.5°C T_{op} or 29.8°C ET which is higher by 0.7°C T_{op} / 2.7°C ET compared to the comfort temperature for the schools studied in Danang. Two possible conclusions are generated: firstly, the comfortable temperatures/range from the statistical analysis of subjective responses in the real environment are 4-5°C higher than the set point/range implemented in the national construction standards.; secondly, the differences in research results between 2012 and 2017 could be attributed to variations of climate and geographic location; and building type (Djamila, et al., 2012).

Table 3. Neutral temperatures and comfort ranges of the Vietnamese found in Vietnam

	City	Year	Season	Building type	Cooling	Method	Neutral temperature (°C)	Comfort zone (°C)
Hung Dang	Ho Chi Minh City	2017	Warm	Residence	Natural	Field study	28.5 (T_{OP}), 29.8 (ET)	
Tuan Nguyen	Danang	2012	Warm	School	Natural	Field study	27.9 (T_{OP}), 27.1 (ET)	
Hang Nguyen	Hanoi	2003	Cold			Experiments		24 - 29 (Ta)

The second comparison relates to studies on comfort for residential buildings over the wider tropics in SE Asia. Most researchers approached the issue by carrying out empirical studies and then they indicated that the observed thermal neutralities vary significantly over SE Asia.

The comfortable operative temperature calculated here from the equation (1) is 0.7°C lower than that determined by Henry (2000) in Jakarta, Indonesia and by 1.5°C compared to the work of Harimi (2007) in Kota Kinabalu, Malaysia. However, it is higher by 2.9°C T_a compared to the work of Ballantyne (1967) in Port Moresby; by 1.5°C compared to N.H. Wong (2000) in Singapore; and by 0.5°C T_a compared to Preechaya (2011) in Bangkok, Thailand.

The thermal neutrality in those studies is similar to the study presented here and also of deDear in 1990 for housing. It is noted that the neutral temperatures found in Singapore, Indonesia (1993), and Thailand were analysed from a combination of both dry and wet seasons. All results indicate that the observed thermal comfort in naturally ventilated buildings, particularly dwellings in hot humid climates, is divergent from the prediction of the PMV model and the implementation of international and local standards.

A review of the works of Henry Feriadi (2004) and de Dear (1994) found that the preferred temperatures for the occupants were at the intersection of two probit lines determined for two trends – "want to be cooler" and "want to be warmer". However, the observed data in HCMC show some variation; for instance, the subjects did not encounter conditions in which their preference would be "want to be warmer". Thus, the identification of preferred temperature in HCMC has to use a modification of the typical approach shown in Figure 10. The temperature thus determined to be preferred by occupants is 27.5°C which is 1.5°C and 4°C higher than those found in naturally ventilated houses in Jogjakarta, Indonesia (Feriadi & Wong, 2004) and in air controlled office buildings in Townsville, Australia (Dear & Fountain, 1994) respectively.

Table 4. Neutral temperatures of the subjects in NV residential buildings in the tropics

	City	Country	Year	Building type	Method	Neutral temperature (°C)	Preferred temperature (°C)	Comfort zones (°C)
Ballantyne	Port Moresby		1967	Residence	Field study	25.6 (Ta)		
	Port Moresby		1979		Climate chamber	26.7 (Ta)		
Richard deDear	Singapore	Singapore	1990	Residence	Field study	28.5 (TOP)		
Nuy Hien Wong	Singapore	Singapore	2000	Public housing	Field study	26.9 (TOP)		
Henry Feriadi	Jakarta	Indonesia	2000-2001	Residence	Field study	29.2 (TOP)	26.0 (TOP)	
Preechaya Rangsiraksa	Bangkok	Thailand	2002-2003	Residence + Office	Field study	28 (Ta)		25.5 - 30.5 (Ta)
Harimi Djamila	Kota Kinabalu	Malaysia	2007-2008	Residence	Field study	30.2 (Ta)		
Hung Dang	Ho Chi Minh City	Vietnam	2017	Residence	Field study	28.5 (TOP), 29.8 (ET)	27.5 (TOP)	31.5 (TOP)-upper limit

The difference between the three sets of findings can be plausibly interpreted as arising from the following: firstly, the difference between cooling options within the samples: natural ventilation for houses in Vietnam and Indonesia; and mechanical cooling for offices in Australia. Many comprehensive studies around the world have indicated that the distinction between thermal subjective responses in air-conditioning and naturally ventilated buildings arises from the variable context of the environment, thermal experiences, and expectations of future thermal desire (Brager & de Dear, 1998). Therefore, in field experiments by de Dear and Fountain in 1994, the temperatures for neutrality and preference found in air conditioning offices are far lower than those found in free-running houses in HCMC. Secondly, for the observed data in Jogjakarta, they were collected in both rainy and sunny seasons. Under a cooler condition in wet months, the samples in a field study of Henry Feriadi showed a preference for warmer in the investigated environment. Consequently, the different characteristic of seasonal data affects divergence in the analytical result of two studies besides reasons of varying climate and demographics.

The authors here have attempted to reconcile some variations in data and analysis with those examples from similar studies and of similar environments in SE Asia, however, there are variations which could prove significant. In particular, it is important in the particular location of Vietnam to understand clearly what occupant sensations and expectations are likely to be as this has impacts on demand for and use of air conditioning systems.

6. Conclusion

The field study undertaken considered both architectural design typologies and also environmental conditions giving rise to comfort/discomfort sensations. These were conducted in the shophouses during warm months in HCMC. The conclusions as follows:

- The indoor and outdoor climatic conditions of the shophouse dwellings were not beneficial for thermal comfort of the occupants with hot air temperature, high solar loads, and low air movement. The thermal environment in buildings strongly correlated with changes in the surrounding climate.
- The neutral and preferred temperatures were found at 28.5°C and 27.5°C T_{op} respectively; with the upper limit of comfort ranging up to 31.5°C. These findings show a level of variability compared to previous studies in Vietnam and other countries in SE Asia.

The authors suggest that the reasons result from variations of building type, climate, characteristic of data, and demographics. This would indicate a need for further study.

- For indoor thermal comfort, there is a significant divergence of thermal neutrality predicted from the observed data and heat balance model. The deviation of comfort temperature is 1.2°C T_{op}.
- The paper shows a knowledge gap in the study of comfortable environments for naturally ventilated and air-conditioned buildings in Vietnam, particularly lacking is information for naturally ventilated residences either from empirical or experimental approaches. The existing efforts in this research field are significant, but still very few in number.
- The comfort temperature/range determined by the field study are significantly different from those prescribed by local and international standards.
- The necessity for further field studies and analysis in cool season is evident in order to achieve a comprehensive set of results for thermal comfort for the occupants of residential buildings in HCMC.

7. References

ASHRAE55, 2004. *Thermal environmental conditions for human occupancy.* Atlanta GA: ASHRAE Inc.

Ballantyne, E. R., Hill, R. K. & Spencer, J. W., 1977. Probit analysis of thermal sensation assessments. *International Journal of Biometeorology,* Volume 21, pp. 29-43.

Brager, G. S. & de Dear, R. J., 1998. Thermal adaption in the built environment - a literature review. *Energy and Buildings,* Volume 27, pp. 83-96.

deDear, R. J. d. & Fountain, M. E., 1994. Field experiments on occupant comfort and office thermal environments in a hot humid climate. *ASHRAE Transactions,* Volume 100, pp. 457-475.

deDear, R., Leow, K. & Foo, S., 1991. Thermal comfort in the humid tropics: Field experiments in air-conditioned and naturally ventilated buildings in Singapore. *International Journal of Biometeorology,* Volume 34, pp. 259-265.

Djamila, H., Chu, C.-M. & Kumaresan, S., 2012. A conceptual review on residential thermal comfort in the humid tropics. *Engineering Innovation & Research,* pp. 539-544.

Djamila, H., Chu, C.-M. & Kumaresan, S., 2013. Field study of thermal comfort in residential buildings in the equational hot-humid climate of Malaysia. *Building and Environment,* pp. 133-142.

Downes, N., Rujner, H., Storch, H. & Schmidt, M., 2011. *Spatial indicators for assessing climate risks and opportunities within the environment of Ho Chi Minh City, Vietnam.* WuHan, ISOCARP.

Duc, D., 2016. *Thuc day nang tiet kiem nang luong tai cac cong trinh xay dung.* [Online] Available at: http://bnews.vn/thu-c-da-y-tie-t-kie-m-nang-luo-ng-ta-i-ca-c-cong-tri-nh-xay-dung/29906.html

Feriadi, H. & Wong, N. H., 2004. Thermal comfort for naturally ventilated houses in Indonesia. *Energy and Buildings,* pp. 614-626.

IBST, 2009. *Vietnam Building Code: Natural physical & Climatic data for construction,* Hanoi: Ministry of Construction.

ISO7730, 2005. *Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.* London: British Standards Institution.

Karyono, T. H., 2000. Report on thermal comfort and building energy studies in Jakarta - Indonesia. *Building and Environment,* pp. 77-90.

McIntyre, 1980. *Indoor climate.* London: Applied Science Publishers.

MOC, 2004. *TCXDVN 306: 2004: Dwelling and public buildings - Parameters for micro-climates in the room.* Hanoi: Ministry of Construction.

Moon, K., Downes, N., Rujner, H. & Storch, H., 2009. *Adaption of the urban structure type approach for vulnerability assessment of climate change risks in Ho Chi Minh City, Vietnam.* Porto, ISOCARP.

Nguyen, A. T., 2013. *PhD thesis: Sustainable housing in Vietnam climate responsive design strategies to optimise thermal comfort,* Liege: University of Liege.

Nguyen, H. M. et al., 2003. Thermal comfort zones in the Vietnamese. *Journal of Human Ergol.,* Volume 32, pp. 107-110.

Parkes, M., 2013. *Vietnam residential energy use,* s.l.: Cimigo.

Rangsiraksa, P., 2006. *Thermal comfort in Bangkok residential buildings, Thailand.* Geneva, PLEA.

Thuc, T. et al., 2016. *Climate change and sea level rise scenarios for Vietnam,* Hanoi: MoNRE.

VSQI, 2005. *TCVN 7438:2004: Ergonomics. moderate thermal environments. determination of the PMV and PPD indices and specification of the conditions for thermal comfort.* Hanoi: Ministry of Science and Technology.

Wong, N. H. et al., 2002. Thermal comfort evaluation of naturally ventilated public housing in Singapore. *Building and Environment,* Volume 37, p. 1267 – 1277.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Developing the adaptive model of thermal comfort for offices in the GCC region

Madhavi Indraganti[1] and Djamel Boussaa[1]

[1] Architecture and Urban Planning Department, College of Engineering, Qatar University, Qatar, madhavi@qu.edu.qa; madhavi.indraganti@fulbrightmail.org

Abstract: Escalating building energy expenditure encourages rethinking on thermal comfort delivery in the Gulf Cooperation Council (GCC) countries, in warm desert climate. The GCC states do not have an adaptive comfort standard, or its precursor long term field surveys. Therefore, we carried out thermal comfort field studies in Qatar for thirteen months. In ten typical air-conditioned office buildings, 1174 voluntary subjects completed 3742 questionnaires, while their thermal environments were simultaneously being measured. We found the mean Griffiths comfort temperature to be 24.0 °C. It varied with indoor temperature and seasons. Indoor Griffiths comfort temperature adaptively related with the outdoor temperature. This relationship can be used in buildings of similar nature in the GCC region. The subjects mostly felt cooler sensations. Thermal acceptance was high (82.7 %). The offices had low indoor air movement (median air speed 0.02 m/s), while 80% recorded less than 0.05 m/s. This is below the average air speed of 0.28 m/s, American Society of Heating, Refrigerating and Air-conditioning Engineers permitted. Increased air movement can effectually facilitate an elevated thermal regime, more in sync with outdoor conditions. Adopting variable comfort standards may be advantageous to achieve the building sustainability goals of the GCC nations.

Keywords: Thermal comfort; Adaptive model; Comfort temperature; Office buildings; GCC

1. Introduction

Oil discovery in the 1970s metamorphosed the Arabian desert nations. Cheap energy availability together with wealth and rapid urbanization escalated building energy consumption in the Arabian Gulf countries (International Energy Agency (IEA), 2017). The six Gulf Cooperation Council (GCC) countries form the oil and gas rich heartland of the Persian Gulf. These Middle Eastern countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates (UAE)) together own about 29.3% and 22.3% of world's oil and natural gas reserves (BP, 2016).

1.1. Major challenges

However, growing population and increasing consumerism transformed the Gulf states into key energy consumers (Clemente, 2015). Consequently, due to this overconsumption, the GCC states have large ecological footprints on a global comparison. Notwithstanding vast national income disparities, the GCC states' per capita demand on the Earth's resources is enormous: Qatar, Kuwait, and the UAE have the world's largest ecological footprints (Luomi, 2012). Recent studies exposed the Arabian Gulf region as a specific regional hotspot where climate change, in the absence of significant mitigation, is likely to severely impact human habitability in the future (Pal & Eltahir, 2015).

The GCC countries had only 0.7% of the world population in 2014. They contribute to 2.9% of the global greenhouse gas emissions, which is higher than European Union (EU) and the Middle East averages (Figure. 1) (International Energy Agency (IEA), 2017). The energy consumption in buildings (residential, commercial and public) in the GCC countries is shooting up. It increased by 112 – 289% in 2000-14, (much higher than EU or world averages) (Figure. 1b). About 70 – 80% of the building energy is used for air conditioning (Budaiwi, Abdou, & Al-Homoud, 2013). Applying the adaptive model significantly lowers the energy consumption in buildings, if used for the indoor environmental control or to adjust design decisions (Nicol & Humphreys, 2002; de Dear & Brager, 1998).

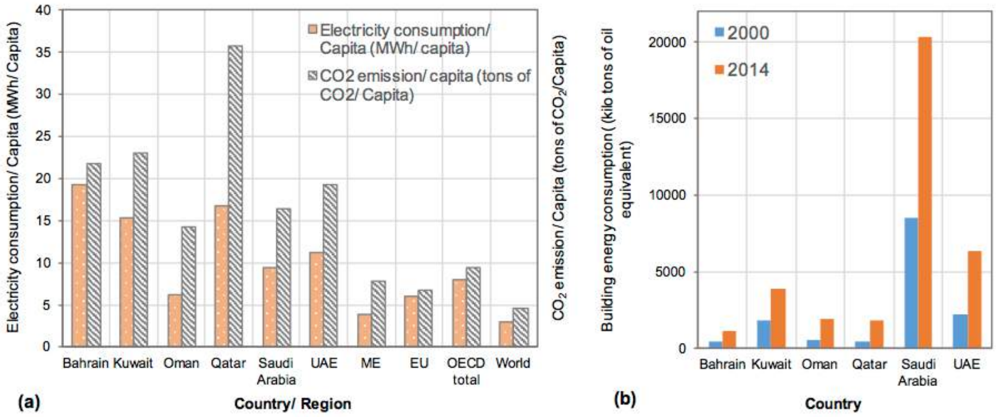


Figure. 1 (a) Electricity consumption and CO2 emissions/ capita in GCC nations compared to the Middle Eastern, OECD (Organization for Economic Co-operation and Development), EU nations and World (data source (International Energy Agency (IEA), 2017)), (b) Rapid growth in building (residential, commercial and public) energy consumption across the GCC (data source (Budaiwi, Abdou, & Al-Homoud, 2013)).

Observable, the GCC region has energy surplus, but saddling along are subsidized low power tariffs and mounting building energy demands (Rodriguez, Pant, & Flores, 2015). Cheap tariffs adopted for various socio-political reasons are costly, highly inefficient and tend to be regressive (Fattouha & El-Katiria, 2013). As Clemente (Clemente, 2015) notes, this situation puts the GCC even more on a collision course with de Tocqueville's "Principle of Rising Expectations" that will reverberate across the globe. Griffiths (Griffiths S. , 2017) echoed similar concerns about the energy dynamics of this region having long lasting impacts on the global energy system.

The regional climate of the GCC is rapidly changing because of human activities from year on year and decade to decade. This has lasting implications on socio-political and economic stability, food, and water (Al-Maamary, Kazem, & Chaichan, 2017). As a result, the GCC countries are adopting a more pro-active approach towards ecological modernization, wherein energy is the key pillar. However, this reorientation has not yet resulted in the development of consistent strategies and policies (Reiche, 2010).

1.2. Key knowledge gaps and literature review

Barring a small pocket, the GCC region has warm desert climate throughout (BWh in Köppen-Geiger classification). However, architecture especially of offices in the Gulf states follows the West with large glass facades ignoring the local harsh climate or energy expenditure (Radhi & Sharples, 2008). As oil prices plummeted and electricity demand increased, sustainability gained currency for some years, with UAE leading the GCC in the forefront (Reiche, 2010; Asif, 2016; Ministry of Development Planning and Statistics, Qatar, 2016). Importantly, the energy use policies adopted in this region have a significant bearing on the future world energy scenarios/ targets (World Energy Council, 2016).

Further, literature points to the enforcement of customized and stringent building standards and codes as a top priority for the GCC, as tariff-based strategies will be less successful in these affluent states (Griffiths S. , 2017; Meier, Darwish, & Sabeeh, 2013). It is important to note that the GCC nations neither have the adaptive environmental comfort standards nor the long term field studies that precede one (Kharama (Qatar General Electricity & Water Corporation), 2010; Dubai Municipality, 2011; SBCNC, 2007). This are major knowledge gaps.

Moreover, researchers identified that thermal insulation regulation makes a small impact on thermal comfort (Radhi, Eltrapolsi, & Sharples, Will energy regulations in the Gulf States make buildings more comfortable – A scoping study of residential buildings, 2009). On the other hand, new buildings in Qatar are advised to follow the Global Sustainability Assessment System (GSAS 2015) recommendations and guidelines. This is a performance-based green building assessment/ rating system (2015). It is neither mandatory nor is an adaptive standard. Similar is the case with other GCC states (SBCNC, 2007) (Radhi & Sharples, 2008) (Dubai Municipality, 2011) (Reiche, 2010).

In the absence of customized standards, the GCC countries follow American and European standards (ASHRAE, 2010; CEN:15251, 2007). A large body of thermal comfort research is concentrated in the USA, Europe and Australia and some parts of Asia (McCartney & Nicol, 2002) (Nicol & Humphreys, 2010; de Dear & Brager, 1998). This resulted in the development of the adaptive comfort standards as proposed by ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) and CEN (Commite European de Normalisation) for the naturally ventilated buildings (ASHRAE, 2010; CEN:15251, 2007). First-hand, robust field study data from real buildings forms the basis for an adaptive model. In addition, to study the seasonal variations in comfort temperature, we need long-term recordings of actual indoor environments and simultaneous thermal perceptions. This paper addresses this knowledge gap.

Moreover, comfort temperatures in the GCC and Qatari offices are not yet investigated based on yearlong data. Our recent office thermal comfort study explained the comfort temperature in summer in Qatar (Indraganti & Boussaa, 2017). This is a short term study and has thus not investigated the relationship between comfort temperature and outdoor conditions.

Thermal comfort effects both health and productivity of occupants in buildings. However, a few studies in other Middle Eastern nations reported the prevailing indoor/ comfort temperatures in various building types and under different modes of environmental control (Heidari & Sharples, 2002) (Heidari, 2008) (Kotbi, King, & Prasad, 2012) (Alshaikh, Roaf, & Smith, 2008) (Khodakarami & Knight, 2008) (Fadeyi, Alkhaja, Sulayem, & Abu-Hijleh, 2014) (Kotbi, King, & Prasad, 2012) (Table 1). Most of these studies were done for a limited period in air-conditioned (AC) non-office buildings resulting from small datasets, with one study covering only naturally ventilated (NV) offices in neighboring Iran.

On the other hand, comfort perceptions, expectations and adaptation in offices differ from those in other building types investigated such as mosques and residences. The comfort conditions in air-conditioned offices round the year may be quite varying, requiring investigation through long-term robust data collection. Therefore, with an objective to develop (a) an adaptive model of thermal comfort and (b) to study the thermal feelings of occupants, we conducted year-long thermal comfort field studies in ten office buildings in Doha, Qatar. The present paper elucidates these results.

Table 1. A Literature review of thermal comfort studies in the Middle East

Researcher	Year	Location	Building type	Number of buildings	Number of datasets	Indoor climate conditioning	Study period	Indoor temperature (mean) (°C)	Comfort temperature (°C)	Adaptive model
Khodakarami and Knight [32]	2008	Illam, Iran	Hospitals	4	.-	AC	Aug 2005, Sep 2005	17.5 – 23.7 (recommended)	None	None
Heidari [31]	2008	Tehran, Iran	Offices	2	631	NV and AC	July, 2004		24.6 (AC) 26.2 (NV)	None
Fadeyi et al. [33]	2014	Dubai and Fujairah,UAE	Elementary schools	16	.-	AC	April 2012- Feb 2013	20.5 1 – 27.7 (24.5)	None	None
Heidari and Sharples [29]	2002	Illam, Iran	Houses	-	891	NV	July, August December 1998	15.4 – 32.7 (30 and 20)	28.4	Regression line
Heidari and Sharples [29]	2002	Illam, Iran	Offices	-	3819	NV	1999	20.0 – 29.0 (23.9)	26.7	Regression line
Al-Sheikh et al. [30]	2014	Dammam, Saudi Arabia	Houses	17	480	AC	August, 2013	19.9 – 35.3 (27.0)	None	None
Kotbi et al. [34]	2012	Riyadh, Saudi Arabia	Mosques	1	422	AC	July, 2011	24.9 – 19.1 (21.7)	None	None
Indraganti and Boussaa [28]	2017	Doha, Qatar	Offices	9	1926	AC	May-Sep 2016	19.6–26.8 (23.7)	24.1	None

2. Methods

Doha (N25° 17’ and E51° 32’), is a coastal city in Qatar with hot desert climate and long hot-humid summer (May- September). Winter (December – February) is mild and Spring (March, April) and Autumn (October, November) are warm, as commonly regarded by the locals. We conducted the field study from January 2016 – January 2017.

2.1. Buildings studied

Spread across the city, ten typical office buildings (named A1- A10) that permitted the survey were selected (Table 2). Four of them were government university office buildings (A5, A7-A9) while the rest housed private company offices. Heating, ventilation and air-conditioning (HVAC) systems were provided in all of them. Seven buildings had operable windows while the rest had only fixed glazing. About 10% of the occupants sat close to the windows and seldom operated them in winter and cooler seasons. Excepting A3, all other buildings had centralized HVAC systems (Table 2). Offices in A4 and A10 moved and the survey was continued in the new premises, A3 and A6 respectively. Poor response after three months prevented us from continuing the investigation in A7. We collected 3742 datasets in total.

2.2. The field survey

Simultaneously with the interviews, we recorded the subjects’ clothing and activity on checklists and the status of their environmental controls as binary data, while they completed the paper questionnaires. Thermal data were measured with high precision calibrated digital equipment. They were mounted on a stand (MS). We measured air and globe temperatures,

CO_2 concentration, relative humidity, air velocity, lighting and noise levels at 1.1m level from the floor (Indraganti & Boussaa, 2017) (Figure 2a).

Table 2. Details of the buildings surveyed

Building name	Ownership	Building envelope	Number of stories	Floors Surveyed	HVAC operation	Type of window	Duration of survey (months)	Data collected (N)
A1	Private	RCC, HBW	5	2 to 5	Centralized	Operable	12	995
A2	Private	RCC, HBW	6	2 to 4	Centralized	Operable	12	783
A3	Private	RCC, HBW	3	2	Split	Operable	3	28
A4	Private	RCC, HBW	2	2	Centralized	Operable	8	217
A5	Public	RCC, HBW	2	1, 2	Centralized	Operable	12	413
A6	Private	SSF, CGW	16	16	Centralized	Fixed	5	302
A7	Public	RCC, HBW	3	2	Centralized	Operable	3	25
A8	Public	RCC, HBW	2	1, 2	Centralized	Operable	12	381
A9	Public	RCC, HBW	3	2	Centralized	Fixed	12	73
A10	Private	SSF, CGW	51	33, 34, 40	Centralized	Fixed	7	525

(N: Sample size; RCC: Reinforced cement concrete frame; HBW: Hollow block wall; SSF: Structural steel frame work; CGW: Curtain glass wall)

Figure 2. Thermal comfort survey (a). The instrument setup (b) process of survey data collection (c) instruments at a workstation group (d-g) typical environments surveyed.

A black painted table tennis ball with a thermal probe at its center was used to measure the globe temperature. Outdoor temperature and humidity were obtained from a meteorological website www.wunderground.com. Their recording station is about 20 - 25 km from the investigated buildings. The questionnaire was in English with the subjective scales as listed in Table 3 (Indraganti & Boussaa, 2017). The questionnaire was modelled after an earlier research (McCartney & Nicol, 2002) (Indraganti M. , Ooka, Rijal, & Brager, 2014) so as to enable comparisons. A part of the current research data collected during summer is presented along with the building and instrument details in (Indraganti & Boussaa, 2017).

Table 3. Subjective thermal scales used

Scale value	Description of scale Thermal sensation (TSV)	Thermal preference (TP)	Thermal acceptability (TA)
3	Hot		
2	Warm	Much cooler	
1	Slightly warm	A bit cooler	Unacceptable
0	Neutral	No change	Acceptable
-1	Slightly cool	A bit warmer	
-2	Cool	Much warmer	
-3	Cold		

We interviewed the subjects seated in open plan offices where 1-5 workstations were laid out together. The MS was placed on a subject's table and 1-5 persons sitting close by responded at the same time. After about 7 -10 minutes of settling, the recordings were noted. Then MS was then moved to the next group of workstations, thus sequentially covering the entire floor (Figure 2). We ensured that MS was away from direct sunlight, exterior walls or active computer screens/ electrical gadgets. The first author conducted all the interviews between 8:00 – 17:00 hours on working days (Monday – Friday), once every month for 13 months in the buildings. This was a large transverse survey. The subjects participated voluntarily and as a result, their number varied slightly in each month.

2.3. Sample size and description

We gathered 3742 completed questionnaires and the corresponding thermal measurements from 1174 occupants (64.1% men and 421 women). The subjects were in the age group of 18 - 64 years (mean age = 32.9 years, standard deviation, SD = 8.9). There are no significant gender differences in different age-groups. About 75% data were provided by Indians, Filipinos, Egyptians, Sri Lankans, Jordanians, French and Qataris, while the rest was from subjects of 44 different nationalities.

2.4. Clothing insulation and metabolic activity of subjects

We estimated the total clothing insulation using the summation method (ASHRAE, 2010) and other reports for Western, Indian and Middle Eastern ensembles (Indraganti M. , Lee, Zhang, & Arens, 2015; Indraganti M. , Lee, Zhang, & Arens, 2016; Al-ajmi, Loveday, Bedwell, & Havenith, 2008; Havenith, et al., 2015) (Table 4). We also added an upholstery insulation of 0.15 clo to all seated subjects and the undergarment's insulation for everybody. About 16% subjects were in non-western clothing such as abaya, hijab, chudidar-kurta (females) and thob, shamk, chudidar-kurta, (males). Majority (89.4 %) of them were women subjects.

Non-western clothing has higher insulation by 0.52 clo than western clothing on an average (Figure 3 a). The difference is statistically significant at 95% confidence interval (CI). Metabolic activity varied from 0.8 – 1.7 Met (Table 4). Clothing insulation was found to be higher when the dress code was imposed in both the genders (Figure 3 b). The images of Middle Eastern and Indian ensembles observed in the field are shown in Figure 2 d,e and Indraganti and Boussaa (Indraganti & Boussaa, 2017).

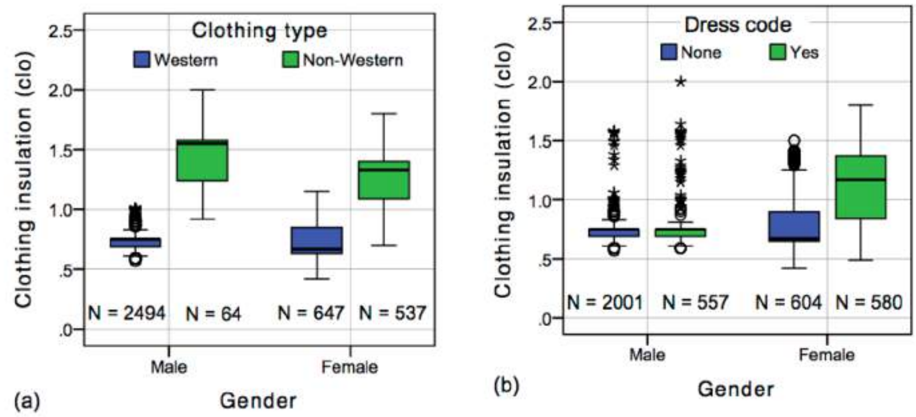


Figure 3. Box plots of clothing insulation for different (a) clothing types (b) dress code scenarios across both genders.

Table 4. Descriptive statistics of outdoor and indoor environmental and personal variables

Variable	Mean	SD
T_o (°C)	**30.8**	**6.5**
T_r (°C)	**30.7**	**6.4**
RH_o (%)	**47.3**	**12.6**
AH_o (g_w/kg_{da})	**13.37**	**4.80**
T_i (°C)	**23.8**	**1.2**
T_g (°C)	**23.4**	**1.2**
RH (%)	**45.4**	**6.9**
AH (g_w/kg_{da})	**8.24**	**1.28**
V_a (m/s)	**0.04**	**0.06**
I_{cl_tot} (clo)	**0.81**	**0.23**
Activity (Met)	**2.3**	**1.1**

N = Sample size; SD: standard deviation; T_o: Outdoor temperature; T_r: Outdoor running mean temperature; RH_o: Outdoor relative humidity; T_i: Indoor air temperature; T_g: Indoor globe temperature; RH: Indoor relative humidity; AH_o and AH: Outdoor and indoor absolute humidity; V_a: Indoor air velocity; I_{cl_tot} : Subject's total clothing insulation

3. Analysis of outdoor and indoor conditions

3.1. Outdoor and indoor environments

Seasonal variation in outdoor conditions was very high, while the indoor conditions remained less variable (Table 4). Mean outdoor temperature was high with moderate to high humidity during the survey excepting in winter months. Indoor globe temperature averaged at 23.4 °C (SD = 1.2) (Figure 4). The indoor conditions in Doha offices are comparable to the Dubai standard limits of 22.5 – 25.5 °C (Dubai Municipality, 2011). Indoor air temperature and globe temperature correlated robustly during the survey (Pearson's correlation coefficient, $r = 0.934$, $p<0.001$) (Figure 5). Therefore, we used globe temperature to analyze the data further. Air velocity was relatively very low in most of the cases with 0.02 m/s being the median air velocity. Indoor humidity ratio was moderate as shown in Table 4. We used IBM SPSS Version 20.0 for analysis. The analytical framework used in this paper is presented in Table 5.

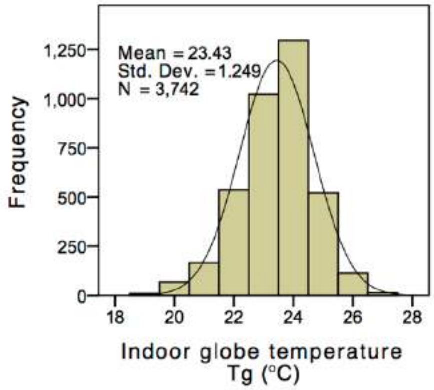


Figure 4. Frequency distribution of indoor globe temperature.

Table 5. The analytical frame work

Step	Process	Function/ Outcome
1	Analysis of outdoor environment	To relate with the indoor conditions
2	Analysis of indoor environment	To relate with outdoor conditions and to estimate comfort temperature
3	Correlation and distribution of subjective thermal responses	To relate with the indoor conditions and to understand subjective warmth/ coolth of the population
4	Logistic regression of thermal sensation and globe temperature	To estimate the comfort zone
5	Linear regression of sensation vote with globe temperature	To obtain the neutral temperature
6	Pooled day survey data analysis	To obtain sensitivity
7	Estimation of running mean temperature	To relate with the comfort temperature
8	Analysis by Griffiths method	Calculation of Comfort temperature
9	Juxtaposing the comfort data with international standards/ studies	Triangulation and comparison with others' results

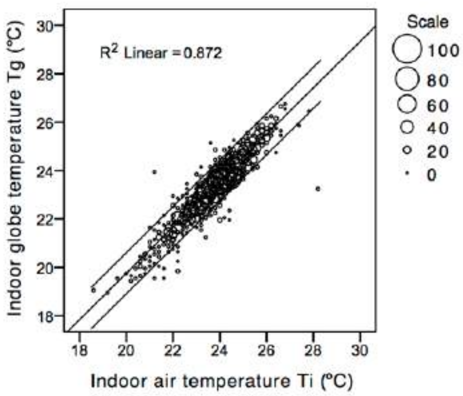


Figure 5. Correlation between indoor air and globe temperatures. Outer lines indicate 95% CI of the regression line.

3.2. Frequency distribution of thermal responses

In response to the thermal environment, people act like 'sensation-thermometers' (p.12) (Nicol, Humphreys, & Roaf, 2012). Therefore, analyzing sensation votes assumes importance. Thermal sensation (TSV) correlated well with thermal preference (TP) (r = 0.71, confidence interval, p<0.01). Conversely, thermal acceptability (TA) displayed very weak relationship with TSV and TP (r = 0.02 and 0.002, p>0.01). Thermal sensation (TSV) averaged at -0.3 (SD = 1.3) with a higher percentage of subjects feeling on the cooler side of neutrality. About 15% expressed cold discomfort (feeling cold and cool) and 9.3% felt warm or hot. A majority i.e., 75.9% felt comfortable (voting at -1, 0 or +1) (Table 6). This is slightly less than the ASHRAE recommended value of 80% (ASHRAE, 2010). As offices are generally maintained cooler compared to the outdoors, most subjects felt either neutral or slightly cool sensations most of the time and preferred 'no change' in the temperature. Mean thermal preference was 0.0 (SD= 0.8). Interestingly, an equal proportion of subjects (about 25% each) preferred cooler and warmer environments from what they were experiencing at the time of voting. While the percent voting comfortable (-1>= TSV <= 1) was slightly less than the ASHRAE recommended value of 80%, the proportion accepting the environment was comparable at 82.7% (ASHRAE, 2010).

3.3. Logit regression for comfort zone

Often times design simulation necessitates the knowledge on the proportion of population that would vote comfortable at a given temperature or scale point. Therefore, we performed logit regression analysis of TSV with globe temperature taking probit as the link function. It resulted in six probit lines (Table 7). These equations represent the probits of proportion (Z(<=TSV)) of votes polled at a given TSV value or less (example: -3 or less or -2 or less) (Figure 6a). The probit regression coefficient for Doha is found to be 0.184/ K. This procedure is clearly laid out in Humphreys et al. (p.235) (Humphreys, Nicol, & Roaf, 2016).

Mean temperature of a probit line is estimated by dividing its y-intercept with its slope (taken as a positive value); such as 2.667/0.184 = 14.5 °C. Inverse of the slope of the equation gives the standard deviation (SD) (Table 7). The probability functions for temperature were then estimated for each of the equations using their respective mean and SD values using the cumulative normal distribution function (CDF.NORMAL). It can also be done in MSEXCEL using the cumulative normal distribution function. We then plotted the probabilities thus obtained against the temperature, which gave a set of six sigmoid curves. These represent the cumulative normal distribution as shown in Figure 6a. These curves help us estimate the probability of voting at a given scale point or lower at various indoor temperatures. For example, at 26 °C, 66% would vote <= 0 (Figure 6a).

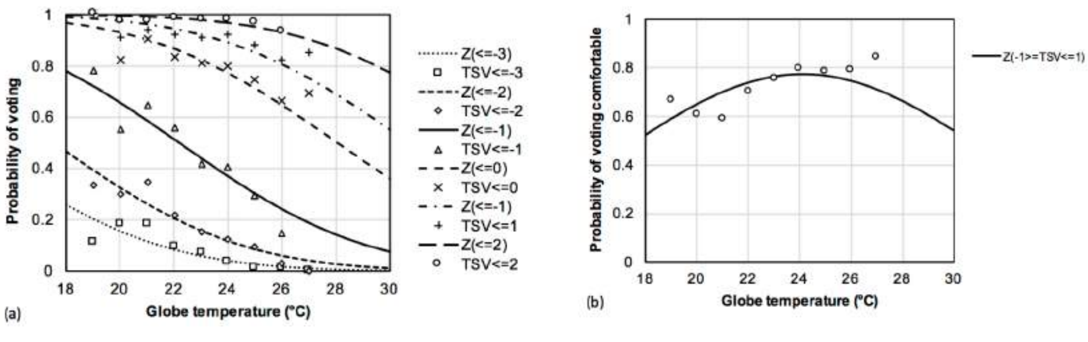


Figure 6. Probit analysis showing the probability of (a) thermal sensation vote, (b) proportion voting comfortable with globe temperature. Marker points indicate the actual proportion voting.

Later, we estimated the probability of subjects voting comfortable (by subtracting the proportion voting <=1 from that of voting <=-2) (Figure 6b). It can be noted that between 24 – 26 °C, about 77 - 75% would feel comfortable (Figure 6b). The marker points shown in Figure 6 represent the actual proportion of subjects voting. These matched closely with the probit lines, indicating the predictive power of regression (Table 7).

Table 6. Distribution of thermal sensation, thermal preference and acceptability votes (N = 3742)

Scale value	Thermal sensation		Thermal preference		Thermal acceptability	
	Description	Voting (%)	Description	Voting (%)	Description	Voting (%)
3	Hot	2.6				
2	Warm	6.7	Much cooler	3.8		
1	Slightly warm	10.7	A bit cooler	20.8	Unacceptable	17.3
0	Neutral	38.4	No change	50.2	Acceptable	82.7
-1	Slightly cool	26.8	A bit warmer	22.5		
-2	Cool	9.1	Much warmer	2.7		
-3	Cold	5.7				

Sample size (N) = 3742; T_g = Globe temperature; SD = Standard deviation; For all equations: (standard error of slope = 0.014; Negelkerke R^2 =0.05; p<0.001)

3.4. Neutral temperature: Linear regression analysis

Neutral temperature indicates the globe temperature at which the occupants vote 'neutral (0)' on the sensation scale. Linear regression is known to be a simple method to find the neutral temperature. It also gives the trend of the mean response over the range of temperatures experienced. Field data can be quickly processed to arrive at the neutral temperature of a population using this method. As is widely used, we employed this method to estimate the neutral temperature to enable comparison. Therefore, we regressed TSV with Tg resulting in the following relationship (Figure 7):

$$\mathbf{TSV = 0.216\ Tg - 5.357} \quad (1)$$

(N = 3742, p<0.001; Coefficient of determination, R2 = 0.041; Standard error of slope, SE = 0.017; F statistic = 160.2)

This yielded a regression neutral temperature (Tn) of 24.8 °C. This is comparable to the mean indoor globe temperature when subjects voted 'neutral TSV' (Tgn) of 23.6 °C (SD = 1.2, N = 1438). This is also within the range of Dubai recommendation (22.5 – 25.5 °C) (Dubai Municipality, 2011). The slope of the equation matched closely with similar research elsewhere. For example, Rijal et al. (Rijal, Humphreys, & Nicol, 2017) obtained a regression coefficient of 0.228/ K in cooling mode, using the yearlong data from Japanese offices. The sensitivity to temperature in Doha and Japan are similar. A summer study in Qatar reported slightly higher slope of 0.283/ K (Indraganti & Boussaa, 2017). Similarly, a Jakarta report mentioned 0.31/ K slope from a sample that included AC and NV buildings (Karyono, 2000). Conversely, occupants in AC buildings in India seem to have displayed lower sensitivity: 0.13 /K change in mean TSV for a unit rise in operative temperature (Manu, Shukla, Rawal, Thomas, & de Dear, 2016). Our result is comparable to that reported in ASHRAE database for AC buildings (de Dear & Brager, 1998).

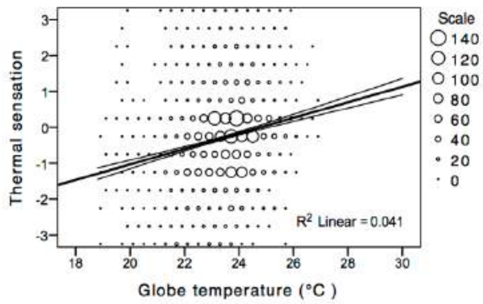


Figure 7. Variation in thermal sensation with globe temperature. Outer lines indicate 95% CI of the slope of the regression.

Linear regression analysis returns a single value of neutral temperature. This is primarily centered around the majority of votes near the midpoint as can be seen from Figure 7. This is understood to be a major drawback (Rijal, Humphreys, & Nicol, 2017) (Indraganti M. , Ooka, Rijal, & Brager, 2014). In addition, there are adaptive errors in regression analysis such as the following: people to tend to constantly adapt as the temperature changes such that the changes in comfort vote remain minimal and vice versa (pp. 145) (Nicol, Humphreys, & Roaf, 2012). Therefore, we estimated the comfort temperature using the Griffiths' method.

3.5. Analysis of within-day changes in subjective warmth and temperature

To improve the precision in the regression coefficient, pooling the quasi-random samples of data collected within a day is found to be useful (pp. 248) (Humphreys, Nicol, & Roaf, 2016). We calculated the mean thermal feeling (T_{fm}) and mean globe temperature (T_{gm}) for all the batches of data collected in a single day in each of the ten buildings for all the days surveyed. These are the building-wise day-survey averages. We then determined two new variables δTf and δT_g. These are obtained by subtracting each of the thermal feeling (Tf) and temperature (T_g) values from their respective day-survey averages (given by $\delta T_f = T_f - T_{fm}$ and $\delta T_g = T_g - T_{gm}$).

We regressed δT_f and δT_g as shown in the scatter plot in Fig. 8. It produced the correctly weighted value of the day survey regression gradient (0.3/ K). As this does not account for the presence of error in the independent variable (δT_g), it needs to be adjusted for the presence of measurement errors in the room temperature. The adjusted regression coefficient is given by:

$$b_{adj} = \frac{b(\sigma^2_{\delta T_g})}{\sigma^2_{\delta T_g} - \sigma^2_{err}} \qquad (2)$$

where b is the regression coefficient of δTf and δTg and $\sigma^2_{\delta T_g}$ is the variance in δTg (square of its SD) and σ^2_{err} is the error variance of δTg taken as 0.158 K2 (pp. 251) (Humphreys, Nicol, & Roaf, 2016) (

Table 8). This equation returned a value of 0.393/ K as adjusted regression coefficient, which is comparable to those obtained from SCATs and ASHRAE databases (Humphreys, Rijal, & Nicol, 2013). The variation is about 0.1/ K (which translates to less than 0.5 K change in temperature. Nicol and Humphreys (Nicol & Humphreys, Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251, 2010) proposed a coefficient of 0.5/K, which is corroborated by robust field study evidence. This was also used in many other studies as well (Rijal, Humphreys, & Nicol, 2017) (Indraganti M. , Ooka, Rijal, & Brager, 2014; Manu, Shukla, Rawal, Thomas, & de Dear, 2016). Therefore, we propose to use 0.5/ K further in this study.

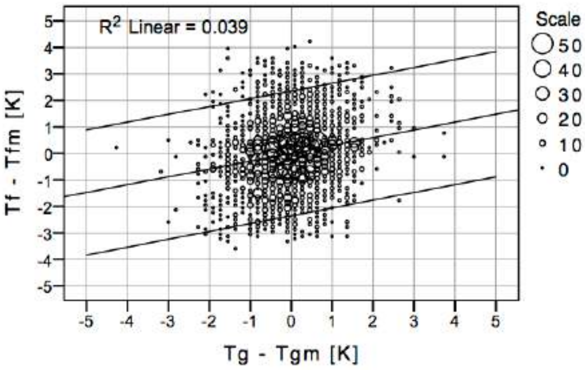


Figure 8. Aggregated regression of the day-surveys. Outer lines indicate the residual standard deviation of the thermal sensation votes (δT_f).

Table 7. Probit analysis of thermal sensation and globe temperature

TSV	Probit regression line	Mean Temperature (°C)	SD
<= -3	**$Z_{(<=-3)} = - 0.184\ T_g + 2.667$**	**14.5**	**5.43**
<= -2	**$Z_{(<=-2)} = - 0.184\ T_g + 3.227$**	**17.5**	**5.43**
<= -1	**$Z_{(<=-1)} = - 0.184\ T_g + 4.084$**	**22.2**	**5.43**
<= 0	**$Z_{(<=0)} = - 0.184\ T_g + 5.163$**	**28.1**	**5.43**
<= 1	**$Z_{(<=1)} = - 0.184\ T_g + 5.650$**	**30.7**	**5.43**
<= 2	**$Z_{(<=2)} = - 0.184\ T_g + 6.721$**	**34.1**	**5.43**

Table 8. Results of building-wise, within day survey regression

Description	(Unit)	Value
Sample size		**3742**
Regression coefficient of δT_f and delta δT_g	**b (/K)**	**0.3 /K**
Standard error of regression	**SE**	**0.024**
Confidence interval	***p***	**<0.001**
Variance in δT_g	**$\sigma^2_{\delta T_g}$ (K^2)**	**0.665**
Error variance in δT_g	**σ^2_{err} ($/K^2$)**	**0.158**
Adjusted regression coefficient	**b_{adj} (/K)**	**0.393**

We observed low regression coefficients when sensation is regressed with indoor temperature as in Figure 7 and Fig. 8. This phenomenon in part is explained through the following: often times in field environments, people undertake several adaptive actions to maintain a near neutral sensation throughout the year (p.270) (Humphreys, Nicol, & Roaf, 2016, p. p 270). These actions could be layering (on/ off) with clothing, switching on/ off heaters, opening/ closing windows, operating thermostat controls etc. This engagement with the immediate environment is in addition to the occupants' psychological adaptation to the prevailing indoor temperature. As a consequence, thermal sensation oscillates rather poorly with indoor temperature leading to low regression coefficients.

4. Results

4.1. Comfort temperature by Griffiths method

Griffiths comfort temperature (hereinafter referred to as comfort temperature) (Tc) can be estimated using Griffiths method which basically relies on the distance the actual vote is from the neutral sensation (Griffiths I. D., 1990; Humphreys, Nicol, & Roaf, 2016). It is given by the relation:

$$Tc = T + (0 - TSV)/ a \quad (3)$$

where Tc is the comfort temperature and T is the indoor temperature and TSV the corresponding sensation vote. While 0 refers to the neutral point of the sensation scale, a is the Griffiths' coefficient, the sensitivity to indoor temperature change, usually taken as 0.5/ K (Humphreys, Nicol, & Roaf, 2016).

Researchers earlier used 0.25, 0.33 and 0.5/ K as coefficients (Rijal, Humphreys, & Nicol, 2017; Rijal, Honjo, Kobayashi, & T, 2013; Humphreys, Rijal, & Nicol, 2013). We have also estimated the Griffiths comfort temperature using these, in addition to the 0.39/ K obtained from within day survey analysis (

Table 8). As can be observed in Table 9, the variation in comfort temperature (Tc) estimated with various coefficients is very little. However, Tc obtained using 0.5/ K slope (mean = 24.0 °C, SD = 2.6, N = 3742) has the lowest standard deviation. And hence is used for further analysis. Rijal et al. (Rijal, Honjo, Kobayashi, & T, 2013) also noticed little change in average comfort temperature by employing coefficients such as 0.25, 033 and 0.5.

Table 9. Descriptive statistics of comfort temperature estimated using various regression coefficients

Regression coefficient (/K)	**Comfort temperature (°C)**	
	Mean	**SD**
0.50	**24.0**	**2.6**
0.39	**24.2**	**3.3**
0.33	**24.3**	**3.8**
0.25	**24.6**	**5.0**

Sample size (N) = 3742; SD = Standard deviation

Mean comfort temperature (Tc) of 24.0 ± 2.6 °C, thus obtained is very similar to the temperature for the highest probability of voting comfortable (Figure 6b) estimated earlier. Both regression neutral temperature of 24.8 °C and the mean indoor globe temperature of 23.6 °C, when subjects voted neutral are also in close proximity to this value. This is also well within the range suggested in Dubai recommendation (Dubai Municipality, 2011). Much similarly, a study in Singapore reported 24.2 °C as neutral operative temperature in AC mode (de Dear & Leow, 1991).

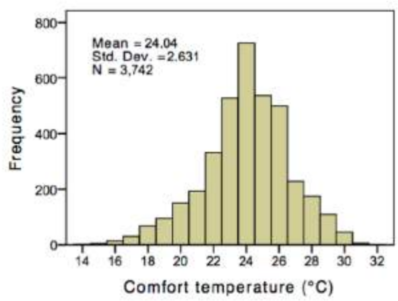


Figure 9. Frequency distribution of Griffiths comfort temperature.

As the comfort vote tends to move away from the center, the comfort temperature moves further from the mean value. As can be noted from Table 6, 24.1 % voted outside the central three categories of the sensation scale. This explains the high variation found in comfort temperature in Doha (Figure 9). Interestingly, this range in T_c is well within the ranges of air and globe temperatures recorded during the survey (Table 4). This lends support to the argument that people take actions (adapt) and find comfort around the range of temperatures they experience over a period of time and vote around neutral most of the time p.270 (Humphreys, Nicol, & Roaf, 2016). Overtime, people are usually able to match their comfort temperature to their normal environment, p.26 (Nicol, Humphreys, & Roaf, 2012). Close association (r = 0.632, p<0.001) noted between the building-wise monthly aggregates of comfort and globe temperatures also explains this (Figure 10).

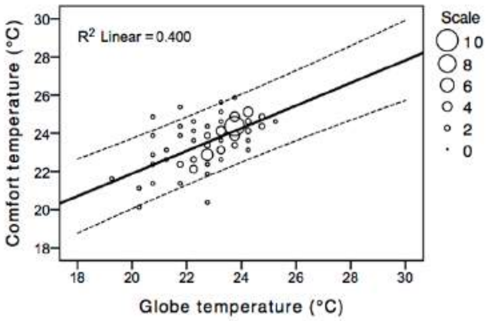


Figure 10. Variation in comfort temperature with globe temperature. Each point is the aggregate value for a building in a month. Outer lines represent 95% of the residual standard deviation of comfort temperature.

Comfort temperature not only depends on the availability and extent of adaptation (for example within a day), but also on the seasonal variations in environmental conditions. For example, as Humphreys et al. (p. 246) (Humphreys, Nicol, & Roaf, 2016) explained, a person can remain neutral at 29 °C and also at 20 °C indoor temperature while dressed in lighter clothing in summer and warmer clothing in winter respectively. Therefore, it is interesting to investigate seasonal changes in comfort temperature vis-à-vis indoor temperature.

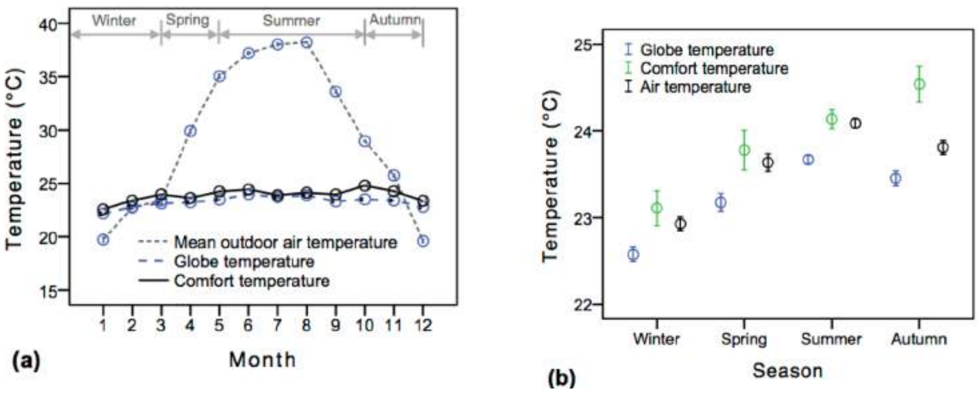


Figure 11 (a). Monthly and (b). seasonal variations in outdoor temperatures and the corresponding indoor and comfort temperatures. Error bars indicate 95% CI.

Seasonal and monthly variations in outdoor temperature and the corresponding indoor and comfort temperatures are shown in Figure 11. While outdoor temperatures varied substantially, we found moderate variation in the indoor and comfort temperatures (Figure 11a). However mild, the seasonal variation in comfort temperature is evident (Figure 11b). While mean thermal sensation vote in all the seasons remained negative, it was lowest in Autumn (mean = -0.54). As a result, mean comfort temperature slightly moved up in Autumn

(24.6 °C) compared to summer (24.1 °C) (Indraganti & Boussaa, 2017). Mean comfort temperature in winter is found to be 23.1 °C and is significantly lower than the rest of the seasons at 95% confidence interval. It also indicates a possible overcooling in summer when the outdoor temperature is very high in Doha. In Japan, an yearly variation of 1.7 K in comfort temperature in cooling mode was reported as against 1.5 K noted in the present study (Rijal, Humphreys, & Nicol, 2017).

4.2. Finding the link between the comfort temperature and the outdoor temperature

An adaptive relationship between the indoor comfort temperature and the prevailing outdoor conditions informs the designers of the appropriateness of the proposed environmental control system design. It is usually represented as a linear regression. To account for the outdoor conditions, an exponentially weighted running mean temperature (Tr) (°C) is used, for it explains the thermal experience better than the daily mean air temperature (To). We calculated the Tr for all the datasets using (Humphreys, Nicol, & Roaf, 2016):

$$\mathbf{T_{r\,(tomorrow)} = (\alpha)\,T_{r\,(yesterday)} + (1-\alpha)\,T_{o\,(today)}} \quad (4)$$

where, α is a constant between 0 and 1, which relates the response of the running mean to the outdoor air temperature, usually assumed to be 0.8 (McCartney & Nicol, 2002; CEN:15251, 2007). This value corresponds to a half-life of approximately 3.5 days. It means that, if there were a unit change in the outdoor mean temperature, the indoor temperature would take about 3.5 days to move half-way towards the new value (pp. 306) (Humphreys, Nicol, & Roaf, 2016). The ASHRAE Appendix –I (ASHRAE, 2015) recommends an α value between 0.6 (mid-latitude climates) and 0.9 (tropics). However, McCartney and Nicol (McCartney & Nicol, 2002) observed the correlation between comfort temperature and outdoor temperature being almost constant in this range and that the coefficient chosen was not critical. Following other earlier works, we used the value of 0.8 in this analysis (McCartney & Nicol, 2002; Rijal, Humphreys, & Nicol, 2017; CEN:15251, 2007). However, alpha is a still a subject needing further investigation. In this study Tr averaged at 30.7 °C (SD = 6.4) (Table 4).

A linear regression of comfort temperature against outdoor running mean temperature resulted in the following adaptive relationship:

$$\mathbf{T_c = 0.049\,T_r + 22.5} \quad (5)$$

(N= 3742, R^2 = 0.015, p<0.001, SE = 0.007)

where, Tc is the indoor comfort temperature, Tr is the outdoor running mean temperature (Figure 12). This equation is useful to predict the comfort temperature at a given outdoor temperature. It also indicates that however slowly, the indoor comfort temperature in Doha changes with the outdoor temperature. This relationship is statistically significant. Nevertheless, the small slope found in this study still reflects small seasonal shifts in comfort temperatures, which are noteworthy. Further, it can become a starting point to implement adaptive control algorithms in lieu of fixed set points for operating the HVAC systems, to save energy, as was reported in McCartney and Nicol (McCartney & Nicol, 2002).

5. Discussion

5.1. Comparison with other's results and international adaptive standards

Table 10 shows a comparison with other international adaptive models proposed after long-term field investigation in offices along with their respective mean comfort temperatures (Rijal, Humphreys, & Nicol, 2017) (Manu, Shukla, Rawal, Thomas, & de Dear, 2016) (Indraganti

M. , Ooka, Rijal, & Brager, 2014) (CEN:15251, 2007) (CIBSE, (The Chartered Institution of Building Services Engineers), 2006) (ASHRAE, 2010) (Heidari & Sharples, 2002).

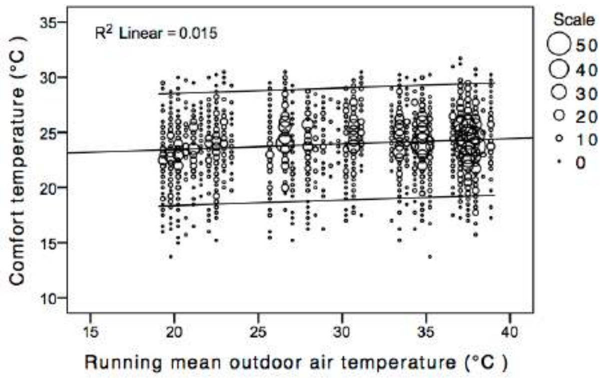


Figure 12 Adaptive relationship between comfort temperature and the running mean outdoor air temperature. Outer lines indicate 95% of the residual standard deviation of comfort temperature.

Table 10. A comparison with other international adaptive models proposed after long-term field investigations in offices.

Location	Researcher/ source	Adaptive model	Mode	Mean T_c (°C)
Qatar	Present study	$T_c = 0.049\ T_r + 22.5$	HVAC	24.0
Japan	Rijal et al. [42]	$T_c = 0.065\ T_r + 23.9$	Heating and cooling	25.5
India	Manu et al. [44]	$T_n = 0.28\ T_r + 17.87$	Mixed mode	
India	Indraganti et al. [35]	$T_c = 0.15\ T_r + 22.1$	HVAC	26.4
India	Indraganti et al. [35]	$T_c = 0.26\ T_r + 21.4$	NV	28.0
Europe	CEN Standard [25]	$T_c = 0.33\ T_r + 22.1$	NV	
Europe	CIBSE Guide [49]	$T_c = 0.09\ T_r + 22.6$	HVAC	
ASHRAE Database	ASHRAE Standard 55 [24]	$T_{op} = 0.31\ T_{mm} + 17.8$	NV	
Iran	Heidari and Sharples [29]	$T_c = 0.292\ T_{mm} + 18.1$	NV	26.7

T_c Comfort temperature; T_r: Running mean temperature; T_{op}: Indoor operative temperature; T_{mm}: Monthly mean outdoor air temperature (°C); NV: Naturally ventilated

The slope of Doha data is close to those obtained with Japan data (0.065/ K) (Rijal, Humphreys, & Nicol, 2017) and European data (0.09/ K) presented in the CIBSE (The Chartered Institution of Building Services Engineers) Guide (CIBSE, (The Chartered Institution of Building Services Engineers), 2006; Nicol & Humphreys, 2007), but much lower than India data (0.15/ K) (Indraganti M. , Ooka, Rijal, & Brager, 2014), all derived based on yearlong studies in air-conditioned offices. It indicates that subjects in Qatar offices are less sensitive to outdoor temperature changes compared to those in Japan, Europe and India respectively. This implies that indoor temperatures in Doha are slightly asynchronous to the climate outside, much unlike the offices in Asia and Europe.

Similar comparison can be made with the adaptive model de Dear and Brager proposed from the ASHRAE database (de Dear & Brager, 1998). They obtained a regression coefficient of 0.31/ K for naturally ventilated (NV) offices on regressing the indoor operative temperature with outdoor monthly mean temperature. Low regression coefficient in Doha can be explained thus: occupants in air-conditioned offices adapted to the pre-selected temperature ordained by the building manager, unlike in NV buildings, where indoors closely follow the outdoor climate.

The comfort temperature obtained in Doha is comparable to that of HVAC offices elsewhere in the world. In India and Japan, it is 1.5 – 4 K higher, perhaps due to elevated air speeds achieved in those offices (Mustapa, Zaki, Rijal, Hagishima, & Ali, 2016) (Damiati, Zaki, Rijal, & Wonorahardjo, 2016) (Indraganti, Ooka, & Rijal, 2013) (Indraganti, Ooka, & Rijal, 2013). In Doha, median air speed was found to be much lower at 0.02 m/s (mean = 0.04 m/s; SD = 0.06, all data) (Table 4).

For the indoor temperatures noted in Qatar, the ASHRAE suggested average air speed is 0.28 m/s (ASHRAE, 2015). It appears that air speeds in Qatari offices can be increased, such that the comfort temperature (vis-a-vis the indoor temperature) can be pushed upwards in warm and hot seasons. This effort can eventually reduce the cooling loads in these seasons. In this context it is pertinent to note that, ASHRAE allows elevated air movement of up to 0.8 m/s, if the operative temperature is below 25.5 °C, even without occupant control. It does not impose any upper limit on air speed if the occupant can control such air movement (ASHRAE, 2015). Moreover, this finding opens opportunities for provision/ improvements in personal environmental controls, to possibly increase the indoor temperature/ comfort temperature.

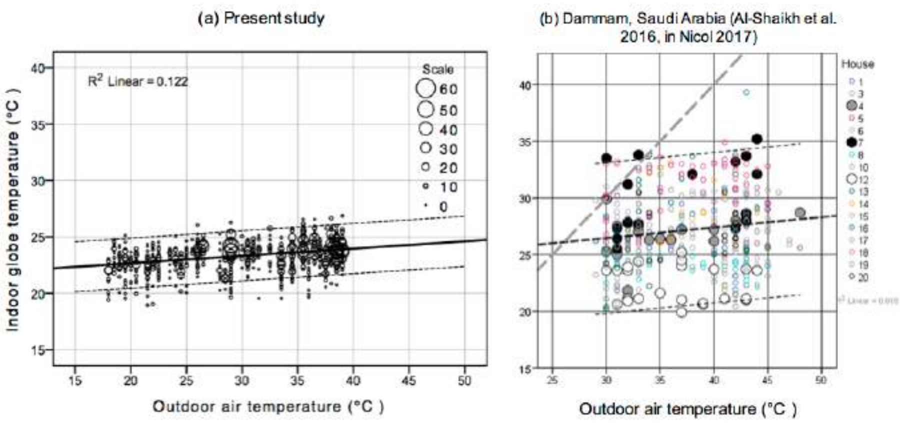


Figure 13. A comparison between (a) the present data and (b) the data from air-conditioned homes in Dammam, Saudi Arabia (Alsheikh et al. (2016) (Alshaikh, Roaf, & Smith, 2008) in Nicol (2017) (Nicol F. , Temperature and adaptive comfort in heated, cooled and free-running dwellings, 2017)).

We juxtaposed the data collected in this study with that from the neighboring Saudi Arabian AC residences (Alshaikh, Roaf, & Smith, 2008) (Figure 13). Nicol (Nicol F. , 2017) reproduced data from Dammam residences Alsheikh et al. (Alshaikh, Roaf, & Smith, 2008) collected. It is evident from Figure 13 that both Doha and Dammam displayed similar temperature sensitivity. Dammam data reflected wider range in indoor temperatures (20 – 35 °C). A back of the envelope calculation using Eq (5) from the data Nicol (Nicol F. , 2017) presented showed the Griffiths comfort temperatures for Dammam ranging broadly (21.2 – 30.3 °C) in contrast to Doha offices (mean Tc = 24.0 $\pm$ 2.6 °C). This possibly indicates limited adaptation in Doha offices, in part due to restricted operation of personal environmental controls, thermostats and other means. A summer study in Doha lends support to this argument. It reported fans being available in 5% of data while their use was found to be limited to 0.05 % of data (Indraganti & Boussaa, 2017).

In Fig. 14, we present a comparison between the adaptive relationships provided in (a) CEN (Commite European de Normalisation) standard (Nicol & Humphreys, 2007; CEN:15251, 2007), (b) Japanese offices (Rijal, Humphreys, & Nicol, 2017) and (c) the present study. Observable, in contrast to (a) and (b) the present study presents the comfort data from hotter regions (where the outdoor temperature is over 30 °C). This is an important contribution. One can also note that the comfort temperature plateaued at about 34 °C of outdoor temperature in Doha, compared to Japan. At the same time, the scatter in Doha is much wider than it is in Japan and Europe, indicating wide choices in comfort temperatures.

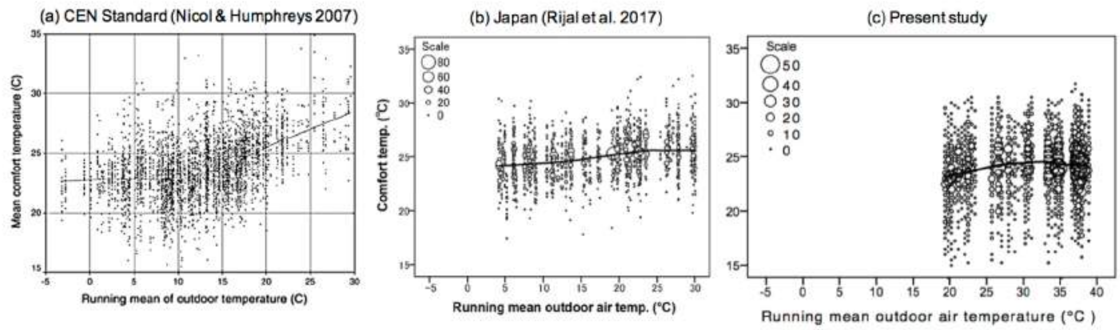


Fig. 14 A comparison between the adaptive relationship in (a) CEN standard (Nicol & Humphreys, 2007), (b) Japanese offices (Rijal, Humphreys, & Nicol, 2017), and (c) Present study.

The sensitivity of comfort temperature to the changes in the prevailing outdoor temperature in Qatar seems to be rather low compared to Asia and Europe. This is in part due to narrow indoor temperature settings. Winter (Winter, 2016) sees this as an 'entanglement (in air-conditioned way of living) bringing entrapment (in low temperatures)'. Therefore, it is beneficial to follow an adaptive algorithm in HVAC control that permits indoor temperatures to track outdoors (e.g. higher in summer and lower in winter). This will save energy substantially, without compromising comfort (McCartney & Nicol, 2002).

A study in Saudi Arabia estimated 11 – 28% reduction in cooling degree-days when base temperature was shifted from 24 °C to 26 °C (Indraganti & Boussaa, 2017). With similar set temperature changes, a simulation study in Bahrain noted 25% reduction in cooling load (Radhi & Sharples, 2008). Another report found occupants being comfortable at 2 K higher temperatures by simply removing their jackets (p.62) (Nicol, Humphreys, & Roaf, 2012).

Hence, it calls for more elastic definitions of comfort, that combine adaptation, clothing and cultural practices so as to significantly reduce the energy demand. This is the appropriate moment to reflect on the history and future of comfort, both as an idea and as a material reality (Chappells & Shove, 2005). What the GCC nations may need is a strong trident of: strict standards, practical tariffs and motivation to save energy. While Qatar's Tarsheed (Be rational) (Kharama (Qatar General Electricity & Water Corporation), 2010) campaign is one step in that direction, an adaptive algorithm may well prove to be a giant leap.

6. Conclusions

We conducted a thermal comfort field study in air-conditioned office buildings in Qatar, for thirteen months. It is a first of its kind study in GCC countries. Following are the conclusions:

1. Qatar has long hot-humid summer and short mild winter. Autumn and spring are brief and warm. Outdoor air temperature and humidity ratio averaged at 30.7 °C and 13.4

g_a/kg_{da} respectively. Indoor air temperature was comparatively cooler with moderate humidity. They varied a little. Mean air temperature and humidity ratios were 23.8 °C and 8.2 g_a/kg_{da}, respectively.

2. Indoor air movement was very low (median 0.02 m/s). Importantly, in 80% cases air movement was slower than 0.05 m/s, below the ASHRAE suggested average speed of 0.28 m/s (ASHRAE, 2015). Therefore, it is possible to increase air speeds to enable increased indoor temperatures.
3. The occupants felt cooler sensation in all the seasons with the average sensation being -0.30, perhaps due to low indoor temperatures. About 75.9% felt comfortable (voting -1 to +1). Conversely, on a direct enquiry, as many as 82.7 % subjects accepted the environment. About 50% subjects preferred *no change* in the thermal environments experienced. We presented probit regression equations to predict the probability of voting on the sensation scale/ comfortable at a given indoor temperature.
4. Linear regression of thermal sensation with indoor globe temperature yielded a neutral temperature of 24.8 °C and a regression gradient of 0.216/ K.
5. The average Griffiths comfort temperature is found to be 24.0 °C with slight seasonal variation.
6. Despite Qatar's climate being hotter when compared to Asia and Europe, the comfort temperature in Qatari offices is found to be lower (by 0.9 - 2.4 K). Similar is the case with indoor temperature, which the comfort temperature closely followed in a cyclic-path dependency.
7. An adaptive relationship between the comfort temperature and the running mean outdoor air temperature was found. Indoor comfort temperature varied by about ½ K for a 10 K change in outdoor temperature. This relationship may be applicable to buildings similar to those investigated. Further, this finding forms a valuable precursor to elaborate future field studies in different building typologies in Qatar, where a stronger association between the comfort temperature and prevailing outdoor conditions can be found.

It is imperative to note that users adapt and negotiate comfort around the mean temperatures at which the buildings are operated; and that the extent of adaptation possible in a building determines its comfort band (Nicol & Humphreys, 2002). These in turn hinge on the building design, its malleability to adaptive operation. Comfort in mechanically ventilated buildings is a manufactured product being delivered to the occupant. Therefore, the comfort discourse may ideally be centered around the occupant adaptation within the built environment and its associated ways of life, rather than merely meeting a narrow band of temperatures (Chappells & Shove, 2005). The sustainability goals of Qatar's National Vision 2030 (Ministry of Development Planning and Statistics, Qatar, 2016) make the adaptive approach to comfort design and delivery compelling. We need more elastic definitions of comfort to positively link the indoors with outdoors. Increased indoor air speeds and variable comfort standards may well be the steps in that direction.

Acknowledgements

We thank all the building owners/ managers/ office heads, and the occupants for their co-operation and participation in the field surveys. We forever regard Late Sreenivas Allakky for his enormous help in data coding and for granting us permissions to survey his offices.

Funding

Qatar National Research Fund through National Priorities Research Program (NPRP -7-143 – 2- 070) funded this research. The Japan Society for Promotion of Science and The University of Tokyo, Japan provided the instruments used.

7. References

Ministry of Development Planning and Statistics, Qatar. (2016, 5). Retrieved from http://www.gsdp.gov.qa/portal/page/portal/gsdp_en/qatar_national_vision/qnv_2030_document

Al-ajmi, F. F., Loveday, D. L., Bedwell, K. H., & Havenith, G. (2008). Thermal insulation and clothing area factors of typical Arabian Gulf clothing ensembles for males and females: Measurements using thermal manikins. *Applied Ergonomics*, 39 (2008) 407–414.

Al-Maamary, H. M., Kazem, H. A., & Chaichan, M. T. (2017). Climate change: The game changer in the Gulf Cooperation Council Region. *Renewable and Sustainable Energy Reviews, 76*, 555–576.

Alshaikh, A., Roaf, S., & Smith, R. (2008). What is the relationship betwen humidity and comfort at high temperatures? In search of new ways of looking at the issue. *8th Windsor Conference: Counting the cost of comfort in a changing world, Network for Comfort and Energy Use in Buildings, http://nceub.org.uk, Windsor, UK, 27-29 July 2008.London.*

ASHRAE. (2010). *ANSI/ ASHRAE Standard 55-2010, Thermal environmental conditions for human occupancy.* Standard, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, Atlanta.

ASHRAE. (2015). ANSI/ASHRAE Addendum d to ANSI/ASHRAE Standard 55-2013.

Asif, M. (2016). Growth and sustainability trends in the buildings sector in the GCC region with particular reference to the KSA and UAE. *Renewable and Sustainable Energy Reviews, 55*, 1267-1273.

BP. (2016). *BP Statistical Review of World Energy June 2016.* London SW1Y 4PD UK: BP p.l.c. 1 St James's Square .

Budaiwi, I. M., Abdou, A. A., & Al-Homoud, M. S. (2013). Envelope retrofit and air-conditioning operational strategies for reduced energy consumption in mosques in hot climates. *Building Simulation , 6*, 33-50.

CEN:15251. (2007). *Indoor environmental input parameters for design and assessment of energy performance of buildings: addressing indoor air quality, thermal environment, lighting and acoustics.* Brussels: Commite European de Normalisation.

Chappells, H., & Shove, E. (2005). Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment. *Building Research & Information , 33*(1), 32-40.

CIBSE, (The Chartered Institution of Building Services Engineers). (2006). *Environmental Design Guide, Vol.A.* London.

Clemente, J. (2015, March 29). The Middle East's Growing Oil Demand Problem. *Forbes*.

Damiati, S. A., Zaki, S. A., Rijal, H. B., & Wonorahardjo, S. (2016). Field study on adaptive thermal comfort in office buildings in Malaysia, Indonesia, Singapore, and Japan during hot and humid season. *Building and Environment, 109*, 208-223 .

de Dear, R. J., & Leow, K. (1991). Thermal comfort in the humid tropics: field experiments in air conditioned and naturally ventilated buildings in Singapore. *International Journal of Bio Meteorology, 34*, 259-65.

de Dear, R., & Brager, G. (1998). Developing an Adaptive Model of Thermal Comfort and Preference, SF-98-7-3 (4106) (RP-884). *ASHRAE Transactions, 104*(1), 1-18.

Dubai Municipality. (2011). *Green Building Regulations and Specifications in the Emirate of Dubai.* Retrieved 1 10, 2017, from Dubai Municipality: http://bit.ly/2p3LhWe

Fadeyi, O., Alkhaja, K., Sulayem, B. M., & Abu-Hijleh, B. (2014). Evaluation of indoor environmental quality conditions in elementary schools' classrooms in the United Arab Emirates. *Frontiers of Architectural Research, 3*, 166-177.

Fattouha, B., & El-Katiria, L. (2013). Energy subsidies in the Middle East and North Africa. *Energy Strategy Reviews, 2*(1), 108–115.

Global Sustainability Assessment System (GSAS). (2015). *GSAS Building Typologies: Design Guidelines 2015 - v2.1.* Doha: Gulf ORganization for Research and Development.

Griffiths, I. D. (1990). *Thermal Comfort in Buildings with Passive Solar Features: Field Studies .* Commission of the European Communities. EN3S-090, University of Surrey Guildford, UK .

Griffiths, S. (2017). A review and assessment of energy policy in the Middle East and North Africa region. *Energy Policy, 102*, 249–269.

Havenith, G., Kulklane, K., Fan, J., Hodder, S., Ouzzhra, Y., Lundgren, K., . . . Loveday, D. (2015). A Database of Static Clothing Thermal Insulation and Vapor Permeability Values of Non-Western Ensembles for Use in ASHRAE Standard 55, ISO 7730, and ISO 9920. *ASHRAE Transactions, 121*(1), 197-215.

Heidari, S. (2008). A big problem – an easy solution. *Air Conditioning and the Low Carbon Cooling Challenge.* Cumberland Lodge, Windsor, UK, 27-29 July: London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk.

Heidari, S., & Sharples, S. (2002). A comparative analysis of short-term and long-term thermal comfort surveys in Iran . *Energy and Buildings, 34*, 607-614.

Humphreys, M. A., Rijal, H. B., & Nicol, J. F. (2013). Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. *Building and Environment, 63*, 40-55.

Humphreys, M., Nicol, F., & Roaf, S. (2016). *Adaptive thermal comfort, Foundations and Analysis.* Oxon, UK: Routledge.

Indraganti, M., & Boussaa, D. (2017). A method to estimate the heating and cooling degree-days for different climatic zones of Saudi Arabia. *Journal of Building Services Engineering Research & Technology , 38*(3), 327-350.

Indraganti, M., & Boussaa, D. (2017). Comfort temperature and occupant adaptive behavior in offices in Qatar during summer. *Energy and Buildings, 150*, 23-36.

Indraganti, M., Lee, J., Zhang, H., & Arens, E. (2015, 1). Thermal adaptation and insulation opportunities provided by different drapes of Indian saris. *Architectural Science Review*, 87–92.

Indraganti, M., Lee, J., Zhang, H., & Arens, E. (2016). Uniqueness of Traditional Indian Ensembles: Clothing insulation of Sari, Salwar-Kameez, Lungi, and Dhoti. *Proc of NCEUB's 9th Windsor Int Conf on "Making Comfort Relevant," April 7-10, Cumberland Lodge, .* Windsor Great Park, UK.

Indraganti, M., Ooka, R., & Rijal, H. B. (2013). Field investigation of comfort temperature in Indian office buildings: a case of Chennai and Hyderabad. *Building and Environment, 65*(7), 195-214.

Indraganti, M., Ooka, R., & Rijal, H. B. (2013). Thermal comfort in offices in summer: Findings from a field study under the 'setsuden' conditions in Tokyo, Japan. *Building and Environment, 61*, 114-132 .

Indraganti, M., Ooka, R., Rijal, H. B., & Brager, G. S. (2014 йил April). Adaptive model of thermal comfort for offices in hot and humid climates of India. *Building and Environment, 74*(4), 39-53. doi:10.1016/j.buildenv.2014.01.002

International Energy Agency (IEA). (2017, 1 9). Retrieved from http://energyatlas.iea.org/#!/profile/WORLD/QAT

Karyono, T. H. (2000). Report on thermal comfort and building energy studies in Jakarta, Indonesia. *Building and Environment, 35*, 77-90.

Kharama (Qatar General Electricity & Water Corporation). (2010). *Regulations for the Installation of Electrical Wiring, Electrical Equipment and Air Conditioning Equipment.* Doha.

Khodakarami, J., & Knight, I. (2008, 3). Required and Current Thermal Conditions for Occupants in Iranian Hospitals. *HVAC&R Research, 14*(2), 175-193.

Kotbi, M., King, S., & Prasad, D. (2012). Validating Fanger's PMV model in a "real" field study. *7th Windsor Conference: The changing context of comfort in an unpredictable world.* Cumberland Lodge, Windsor, UK, 12-15 April: London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk.

Luomi, M. (2012). *Qatar's Natural Sustainability: Plans, Perceptions, and Pitfalls.* Center for International and Regional Studies . Georgetown University School of Foreign Service in Qatar.

Manu, S., Shukla, Y., Rawal, R., Thomas, L. E., & de Dear, R. (2016). Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). *Building and Environment, 98*, 55-70.

McCartney, K. J., & Nicol, J. F. (2002). Developing an adaptive control algorithm for Europe. *Energy and Buildings, 32*, 623–635.

Meier, A., Darwish, M., & Sabeeh, S. (2013). Complexities of saving energy in Qatar. *ECEEE 2013 Summer Study Proceedings– Rethink, Renew, Restart*, 41-46.

Mustapa, M. S., Zaki, S. A., Rijal, H. B., Hagishima, A., & Ali, M. S. (2016). Thermal comfort and occupant adaptive behaviour in Japanese university buildings with free running and cooling mode offices during summer . *Building and Environment, 105*, 332-342 .

Nicol, F. (2017, 2). Temperature and adaptive comfort in heated, cooled and free-running dwellings. *Buidling Research and Information*, 1-15.

Nicol, F. J., & Humphreys, M. A. (2007). Maximum temperatures in European office buildings to avoid heat discomfort. *Solar Energy, 81*, 295-304.

Nicol, F., & Humphreys, M. A. (2010). Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Building and Environment, 45*(1), 11-17.
Nicol, J. F., & Humphreys, A. M. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings, 34*(6), 563-572.
Nicol, J. F., Humphreys, M. A., & Roaf, S. (2012). *Adaptive Thermal Comfort, Principles and Practice.* London, UK: Routledge.
Pal, J. S., & Eltahir, E. A. (2015, 2 26). Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change, 6*, 197-200.
Radhi, H., & Sharples, S. (2008). Developing Standards for Low-Energy Buildings in the Gulf States. *Architectural Science Review, 51*(4), 369-381.
Radhi, H., Eltrapolsi, A., & Sharples, S. (2009). Will energy regulations in the Gulf States make buildings more comfortable – A scoping study of residential buildings. *Applied Energy, 86*, 2531–2539.
Reiche, D. (2010). Energy Policies of Gulf Cooperation Council (GCC) countries—possibilities and limitations of ecological modernization in rentier states. *Energy Policy, 38*, 2395–2403.
Rijal, H. B., Honjo, M., Kobayashi, & T, N. (2013). Investigation of comfort temperature, adaptive model and the window-opening behaviour in Japanese houses. *Architectural Science Review, 56*, 54-69.
Rijal, H. B., Humphreys, M. A., & Nicol, J. F. (2017). Towards an adaptive model for thermal comfort in Japanese offices. *Building Research & Information*(Rethinking on Comfort), 1-13.
Rodriguez, S., Pant, M., & Flores, J. C. (2015). *Energy Price Reforms in the GCC: What Can Be Learned from International Experiences?* Washington: International Monetary Fund.
SBCNC. (2007). *Saudi Building Code Energy Conservation Requirements: 601.* Saudi Building Code National Committee. Riyadh: Government of Saudi Arabia.
Winter, T. (2016). Active cooling and low carbon comfort. *The Journal of Architecture, 21*(3), 418-432.
World Energy Council. (2016). *World Energy Scenarios l 2016: The Grand Transition.*

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Thermal comfort in office buildings during the summer season: Findings from a field study in Kuwait

Rasha W. AlNajjar[1], Adil Al-Mumin[2] and Madhavi Indraganti[3]

[1] Kuwait University, Kuwait, R.w.alnajjar@gmail.com;
[2] Kuwait University, Kuwait, almumin@yahoo.com;
[3] Qatar University, Qatar, madhavi@qu.edu.qa

Abstract: A thermal comfort field study was conducted in four office buildings in Kuwait for four months in the summer of 2016. All the four environmental and two personal variables were measured. Through a paper based survey, a total of 611 responses were collected from 284 different thermal environments. The mean comfort temperature was found to be 22.5 °C. This finding shows that people are very much accustomed to overcooled building environments that lack provisions for thermal adaptation. The subjects adapted mainly through clothing and very little environmental controls which were available to them. The mean clo values of nonwestern clothing was found to be higher than that of the insulation of the western clothing. In 86.6% of the cases, the air speed was below 0.2 m/s. The predicted mean vote significantly overestimated the actual sensation always. An adaptive model specific to Kuwait's climate must be developed and this research is a stepping stone to address this issue. This study calls for elaborate field studies in offices in Kuwait for the development of custom made adaptive comfort standards and a verified thermal comfort scale in Arabic to be uniformly used in surveys in the Middle Eastern Region.

Keywords: Kuwait, Thermal comfort, Office buildings, Adaptive model, Field study

1. Introduction

During the last 50 years, there has been an alarming increase in the worldwide average global temperatures (NRDC, 2017). While 2017 is still not over, a 2% rise is projected for global CO_2 emissions (IEA, 2017). This is devastating for the efforts of environmentalists and scientists that are working on slowing down global warming. Studies have shown that burning fossil fuels to make electricity is the largest source of heat trapping pollutants. With all the distressing factors affecting our environment and the future of our planet, sustainable methods of living need to be adapted. These methods should be implemented in our everyday life and in the buildings we use.

1.1 Relevance to the region and Kuwait

Little research has been done on thermal comfort in the Middle East and North Africa (MENA). Therefore, there still hasn't been an adaptive model created for this climate type and for the area. It is vital that much more research is done in the region for all the seasons to develop an adaptive model based on the unique local practices and cultures. As a result, the research will help us develop a sustainable method specific for the area, culture, clothing type, and climate.

It is important that architects design buildings that identify with the surroundings, climate, and culture of the project. Creating structures that can be controlled by people, architecture should be designed for human adaptation through low energy means. Relying on the Predicted Mean Vote (PMV) as a predictor of thermal comfort is not a solution. The PMV model is too costly to abide by because of its narrow temperature recommendations and heat balance approach.

1.2 Identifying the knowledge gaps

A great deal of international research has been conducted on thermal comfort in office buildings worldwide whereas there is very limited research done on thermal comfort and none in office buildings in Kuwait. . Kuwait's energy expenditure towards environmental control of buildings is equally very high much similar to other GCC countries (Budaiwi, et al., 2013). Therefore field study research leading to the development of the adaptive control algorithms for buildings is very much the need of the hour. This will aid the development of a thermal comfort standard for all building types for the country's unique weather, non-western clothing ensembles, and vast temperature ranges.

1.3 Aims of the research

The aim of this research is to prove that people in Kuwaiti offices adapt to a wider range of temperatures through several mechanisms and that the offices are being overcooled. In this context, a thermal comfort field survey was conducted in Kuwait in summer of 2016. The aim is to investigate the thermal conditions in four office buildings and find the comfort temperature of occupants during the summer season while not overlooking vital variables including gender, age, nationality, and clothing. The study has the following objectives:

1. To investigate the current indoor environmental conditions in Kuwaiti office buildings.
2. To examine the occupants' thermal comfort, preferences and acceptability in offices in Kuwait.
3. To study the effect of other environmental parameters such as air movement on thermal perceptions.
4. To investigate the environmental and behavioral adaptation and evaluate the comfort temperature of building occupants in Kuwait based on the field study data.
5. To investigate the impact of clothing type (western, nonwestern) on occupant's comfort and thermal acceptability.

1.4 Background of Kuwait

Kuwait is located in the desert geographical region and falls on the arid sub continental belt. Kuwait's climate is known by its two main seasons: dry hot long summer and short cool winter with occasional rainfalls. During the summer months dust storms often occur. In addition, the summer is considered to be one of the most uncomfortable seasons in Kuwait, where the shade temperature can reach up to 50 °C.

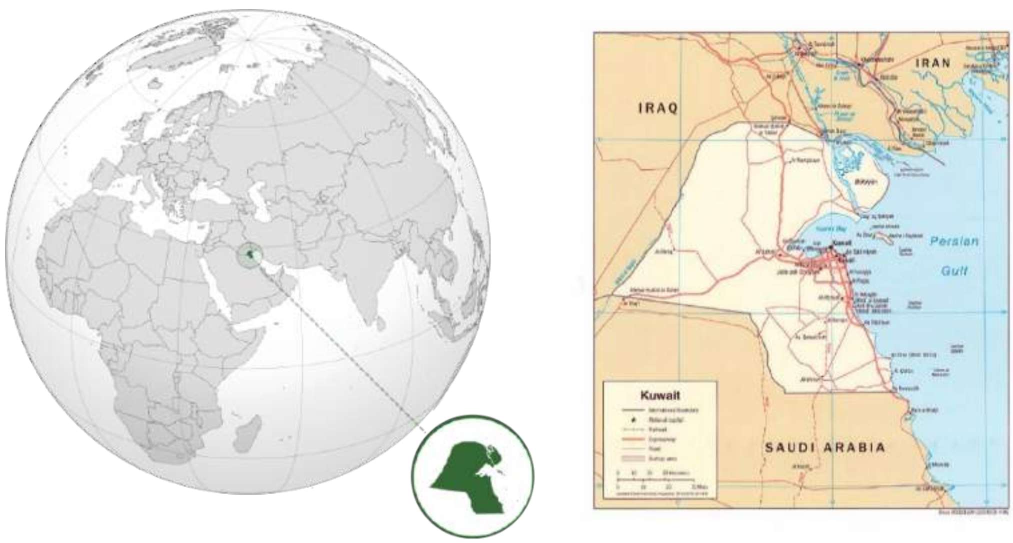


Figure 1. Kuwait's geographical location in the world (Googlemaps, 2016).

Kuwait is known for its variety in clothing ensembles. It is less conservative than other neighboring countries since many women can be found wearing western clothing. Other women choose to wear the "*hijab*" the headscarf with conservative clothing covering the arms and legs. Some choose to wear the "*abaya*" over of their regular clothes. Men are sometimes found in western clothing while often times they are in their "*dishdasha*" and "*ghitra*" which is the traditional clothing of men in the gulf region.

2. Methodology

The survey was conducted during the peak summer months of May, June, July, and August of the year 2016. These months are selected due to their intense discomfort levels, where the temperature reaches its highest. The maximum daily outdoor temperatures on the surveyed days were found to be between 38°C and 51°C with a mean temperature of 43°C **(Wunderground, 2017)**.

2.1 The buildings investigated

Thermal comfort surveys and corresponding thermal measurements were taken in 4 different air-conditioned office buildings in Al-Khaldiya, and Free Trade Zone areas in Kuwait from May 2016 to August 2016. Table 1 explains the buildings investigated and their corresponding details.

Table 1. Buildings investigated with codes and related details.

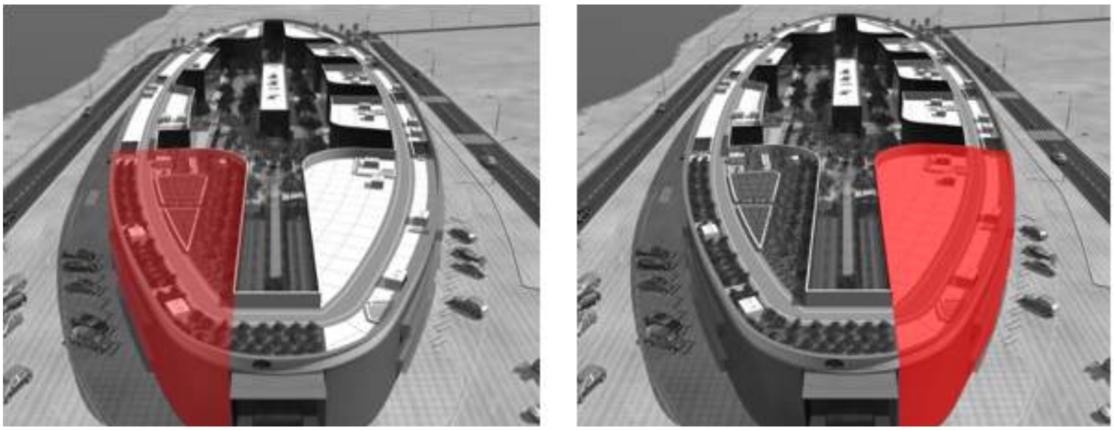
Bldg. Code	Name	Building Type	Air Conditioned	Location	# of Survey months	Investigated Floors
B1	**ALARGAN International Co.**	**Private (LEED[1])**	**Yes**	**Free Trade Zone**	**4**	**G, 1**
B2	**ALARGAN Project Management Co.**	**Private**	**Yes**	**Free Trade Zone**	**4**	**1**
B3	**College of Architecture**	**Government**	**Yes**	**Al-Khaldiya**	**4**	**G, 1**
B4	**Finance and Purchasing Affairs Department**	**Government**	**Yes**	**Al-Khaldiya**	**4**	**G, 2**

[1] Leadership in Energy and Environmental Design

The first office building investigated is ALARGAN International Real Estate Company, a Leadership in Energy and Environmental Design (LEED) Platinum office building labeled "**B1**" located in Free Trade Zone area in Kuwait as shown in Figure 2. The second building investigated is ALARGAN Project Management Company, located in the same cluster of office buildings, opposite of "**B1**" and is not a LEED certified office building labeled as "**B2**".

A. B.

Figure 2. A. ALARGAN buildings surveyed. B. Building location and orientation on site. (Googlemaps, 2017).



C. D.

Figure 3. C. "B1" LEED certified building. D. "B2" non- LEED certified building. Source: ALARGAN Co.

The building scored 13 out of 17 on indoor environmental quality (Figure 4).

Figure 4. ALARGAN headquarters LEED Score Card. Source: (USGBC, 2015).

*Figure 5. "**B1**" ALARGAN International headquarters ground floor plan.★Shows points of thermal measurements taken.*

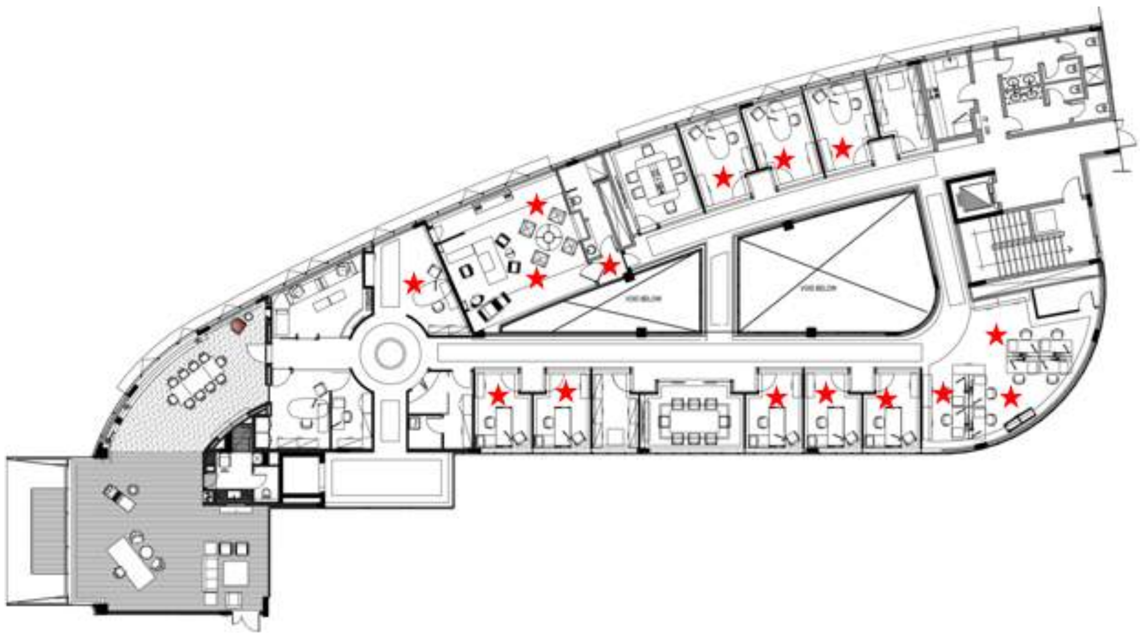


*Figure 6. "**B1**"ALARGAN International headquarters first floor plan.★ Shows points of thermal measurements taken.*

*Figure 7. "**B2**" AREPMC building (Non LEED certified) floor plan located on the first floor. ★Shows points of thermal measurements taken. Source: ALARGAN Co.*

Figure 8. Instrument setup ALARGAN International office interiors where research was conducted.

The Third building labeled "**B3**" is The College of Architecture located in Al-Khaldiya in Kuwait in Kuwait University Campus (Figure 9).

Figure 9. College of Architecture Location and Orientation. (Googlemaps, 2016).

The fourth and final building is The Finance and Purchasing Affairs Department labeled as “**B4**” also located in Al-Khaldiya in Kuwait on Kuwait University Campus (Figure 10).

Figure 10. The finance and purchasing affairs department location and orientation. Source: (Googlemaps, 2016).

Figure 11. “B4” The Finance and Purchasing Affairs Department, Kuwait University, Khaldiya Campus.

2.2 Data collection

The methodology used in this research consists of three major steps:

1. **Survey questionnaire:** used to measure occupant comfort levels.
2. **Observation:** used to observe personal variables and environmental controls in the offices.
3. **Environmental measurement with digital instruments:** used to measure the indoor environmental quality.

2.2.1 Field survey

All the necessary permissions from the heads of departments were obtained prior to the survey. The survey questionnaires to be used for this research were based on Indraganti et al. (2015) and McCartney and Nicol (2002). A briefing on the survey was given to all the subjects prior to their first interview, and no major briefing was necessary later on. This was a paper based survey.

The subjects were surveyed for three consecutive days in a month: in governmental buildings they were surveyed between 9:00 – 14:00 hours and between 9:00 – 17:00 hours in private buildings depending on the office hours. Test times were changed for the three days, if surveys were given in the morning on day one, the next day it was at noon and the third day it was in the afternoon. A new questionnaire was filled by the subject in all the interviews. Only one interview was conducted for each subject in one survey day.

2.2.1.1 The scales used

Table 2. Scales used in thermal comfort surveys conducted.

		Scale Name		
Scale value	**Thermal Sensation**	**Thermal Preference**	**Thermal Acceptance**	**Skin Moisture**
+3	**Hot**			**Profuse**
+2	**Warm**	**Much Cooler**		**Moderate**
+1	**Slightly Warm**	**A Bit Cooler**	**Unacceptable**	**Slightly**
0	**Neutral**	**No Change**	**Acceptable**	**None**
-1	**Slightly Cool**	**A Bit Warmer**		
-2	**Cool**	**Much Warmer**		
-3	**Cold**			

2.2.2 Observation: measurement of personal variables and environmental controls

Each participant's metabolic activity, clothing, use of environmental and personal controls and the behavioral adaptation were noted in all the surveys in the field data sheet.

Table 3. Metabolic rates of various office activities (mets). Used based on the subject's activity in the offices. Source: ANSI/ASHRAE Standard 55-2010 (ASHRAE, 2012).

Activity	Sitting	Sitting/Light activity	Sitting/Heavy work	Standing	Standing working	Moving Around
Metabolic rate (met)	1	1.1	1.2	1.2	1.4	1.7

Furthermore, the nationality and the duration of employment with the respective office of each subject was noted. All the required evidence on the behavioral and environmental adaptation was noted since permissions for photographs was not granted by many subjects involved in the survey.

However, the subjects were asked simple questions to elicit further information in case of finding any peculiar clothing or environmental control or behavioral adaptation undertaken by the subjects and were noted in the field notes.

2.2.3 Environmental measurement of the indoor environments using digital equipment and collection of outdoor environmental data

A set of hand held, calibrated digital instruments were used to measure the indoor environment. The instruments were mounted on a tripod at 1.1 m off the ground for easy transportation. The instrument details are shown in Table 4.

The indoor environmental variables measured during the fields study are:

1. Air temperature (T_a),
2. Globe temperature (T_g),
3. Relative humidity (RH),
4. Air velocity (Av)
5. Carbon –dioxide concentration (CO_2)
6. Noise level (dBa)
7. Light level (lux)

Table 4. Details of the instruments used for the environmental measurement.

Label	Description	Trade Name	Parameter used	Range	Accuracy
Instruments Details					
A	**Hot wire anemometer**	**Kanomax climomaster – 6542**	**Air Velocity**	**0.01-50.0 m/s**	**+/-0.01 m/s**
B	**Probe thermometer with black painted table tennis ball**	**Tr-52i**	**Globe temperature**	**(-60 to 155°C)**	**+/-0.5°C**
C	**Thermo-hygro- CO_2 meter**	**TR-76Ui**	**Air temperature, Humidity, CO_2 level**	**0 to 45°C 10 to 90%RH 0 to 5000 ppm**	**+/- 0.5°C +/-5% +/-50ppm**
D	**Light Meter**	**Testo 545**	**Light level**	**0 to 100000 Lux**	**±8.5 %**
E	**Data logger sound level meter**	**CEM DT-8852**	**Sound level**	**30 dB to 130 dB**	**+/- 1.4 dB**

2.3 Details of instrument setup

The survey was completed in the office buildings specified in the areas where permissions were granted. The instruments were fixed into an instrument setup on a tripod where the measurement probes were at 1.1 m level from the floor when placed on the ground as shown in Figure 12.

Figure 12. Instruments used and instrument setup. ***A:*** *Hot wire anemometer,* ***B:*** *Globe Thermometer,* ***C:*** *Thermo-hygro- CO_2 meter,* ***D:*** *Lux meter,* ***E:*** *Sound meter.*

*Figure 13. Instruments used and instrument setup. **A:** Hot wire anemometer, **B:** Globe Thermometer, **C:** Thermo-hygro- CO_2 meter, **D:** Lux meter, **E:** Sound meter.*

2.4 The subjects

The subjects are all healthy individuals living in Kuwait and are adapted to the surveyed environment. All are assumed to be naturally acclimatized to the climate of Kuwait. All interviewees were voluntarily participating occupants in this survey. The sample size for the four months is 611 samples from 283 different thermal environments. The number of voluntary participants was larger in May and slowly started decreasing in the coming months. This is partially due to the fact that the research was conducted during the summer where many tend to travel during this time period. Participation was affected in June since it corresponded to the holy month of Ramadan.

The data was collected from 47% Kuwaiti nationals, 28% was from Egyptian nationals, 10% Indian nationals, 9% Lebanese nationals, and 6% was from other nationals (Philippines and Palestinians). There were 261 voluntary Kuwaiti subjects of the total 612 (Fig. 14).

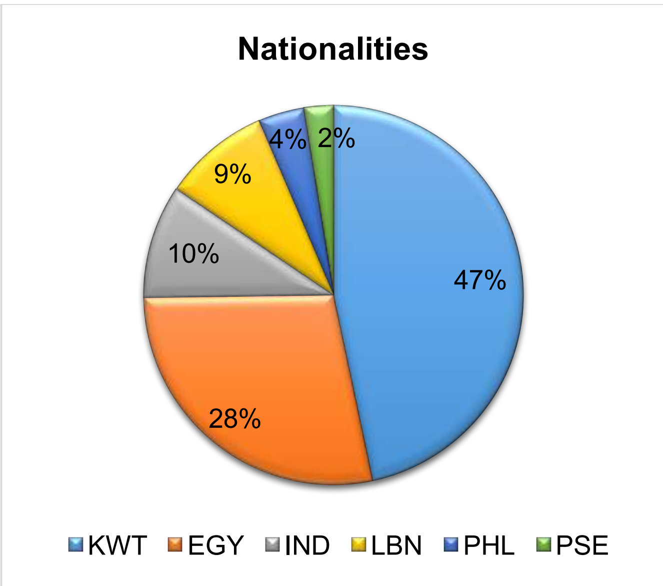


Figure 14. Nationality distribution of subjects.

2.4.1 Age and gender

The respondents are in the age group of 21-60 years of age comprising of 329 females (54%) and 282 males (46%). The average age of females was 31.5 years (SD= 6.5), while the average age of males was 37.1 years (SD= 8.6). Therefore, the average age of males was higher than that of females. Some male and female respondents refused to state their age in the survey.

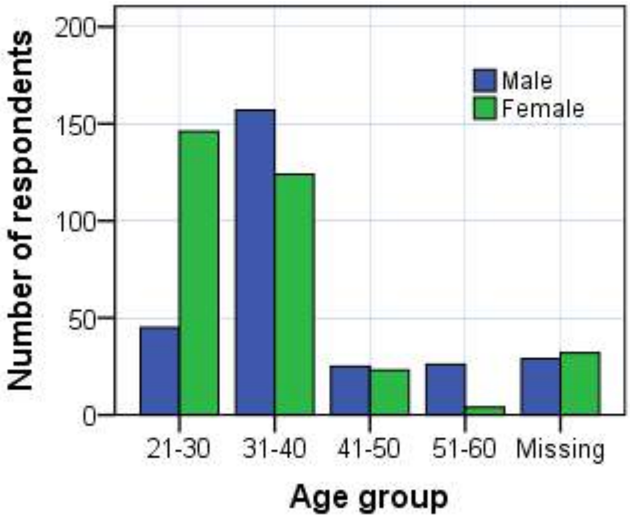


Figure 15. Number of male to female respondents in the specified age groups.

2.5 Estimation of clothing insulation

The clothing insulation values were estimated using the summation formula of $I_{cl\_tot}=\sum I_{clu,i}$ where, I_{cl_tot} was the insulation of the entire ensemble and $I_{clu,i}$ was the insulation of the individual piece of garment. Readily available standard lists were used to calculate western clothing insulations. Traditional Arabian Gulf ensembles were calculated by finding individual clo values of various traditional garments provided in a study done by (Al-ajmi, et al., 2008). Each garment type was then coded with a number corresponding to its thermal insulation and was added to the different layers of clothing to find the sum of the entire ensemble worn by the individual surveyed. The clothing insulation of female subjects during the surveyed summer period was (mean I_{cl_tot}=0.77, SD=0.24), relatively similar to that of the men which was calculated to be (mean I_{cl_tot}=0.78, SD=0.21).

Table 5. Nationality, age and clothing value distribution of the subject sample.

Nationality	Sample size	Gender	Variable	Mean	Std. deviation
Kuwaiti	**(N= 54)**	**Male**	**Age**	**32.2**	**5.49**
			Clothing (clo)	**0.997**	**0.30**
Kuwaiti	**(N=206)**	**Female**	**Age**	**29.9**	**5.57**
			Clothing (clo)	**0.84**	**0.25**
Non-Kuwaiti	**(N= 228)**	**Male**	**Age**	**38.3**	**8.76**
			Clothing (clo)	**0.73**	**0.15**
Non-Kuwaiti	**(N= 123)**	**Female**	**Age**	**34.6**	**6.90**
			Clothing (clo)	**0.67**	**0.18**
All	**(N=611)**		**Age**	**34.1**	**8.01**
			Clothing (clo)	**0.777**	**0.23**

Typical ensembles worn by women during the summer months were very modest (long sleeves, with long pants or long skirts) due to the fact that 63.5% of females wore non-western clothing (ex. hijab, which is an Islamic head covering that requires the covering of arms and legs. Some women even wore Abaya, and niqab). The remaining 36.5% female respondents were in typical western clothing. While only 12.8% of male respondents were in non-western clothing wearing the traditional Kuwaiti ensemble (dishdasha, gitra). The majority of males comprising of 87.2% were in western clothing.

Table 6. Clo value differences between western and nonwestern ensembles worn in Kuwait.

Gender	Clothing type	Mean Insulation (clo)	Sd. deviation
Male	**Non-western**	**1.241**	**0.099**
	Western	**0.714**	**0.129**
Female	**Non- Western**	**0.845**	**0.251**
	Western	**0.652**	**0.173**

Female Kuwaiti respondents were significantly more than the Kuwaiti male respondents. Where 62.6% of the total female respondents were Kuwaiti nationals and only 19.5% of the total male respondents were Kuwaiti nationals. The remaining 37.4% female and 80.5% male respondents were all mixed nationalities. Figure 16 shows the western vs. nonwestern male and women percentages and the average clo value for each ensemble type.

	Male		**Female**			
	Non Western	**Western**	**Non Western**		**Western**	
						
surveyed (%)	**12.8**	**87.2**	**63.5**		**36.5**	
Clo. value	**1.045**	**0.850**	**1.307**	**0.672**	**1.120**	**0.610**

Figure 16. Clothing ensembles found in offices. Images are taken from (fotolia, 2017)*,* (dreamstime, 2017)*,* (pinterest, 2017)*,* (freepik, 2017)*.*

3. Results and discussion

Environmental conditions in the surveyed areas

3.1 Outdoor conditions

Intense discomfort is felt during the summer season in Kuwait due to the high temperatures characterized by the hot and arid climate of this region. Where, dust storms often occur during the summer months along with high temperatures. Relative humidity oscillated between 9% and 51% with 18% as the mean value.

During the surveyed months the maximum daily outdoor temperatures on the surveyed days fluctuated between 38°C and 51°C with a mean temperature of 43°C. The overall daily mean outdoor temperatures were between 30°C and 45°C (Fig. 16).

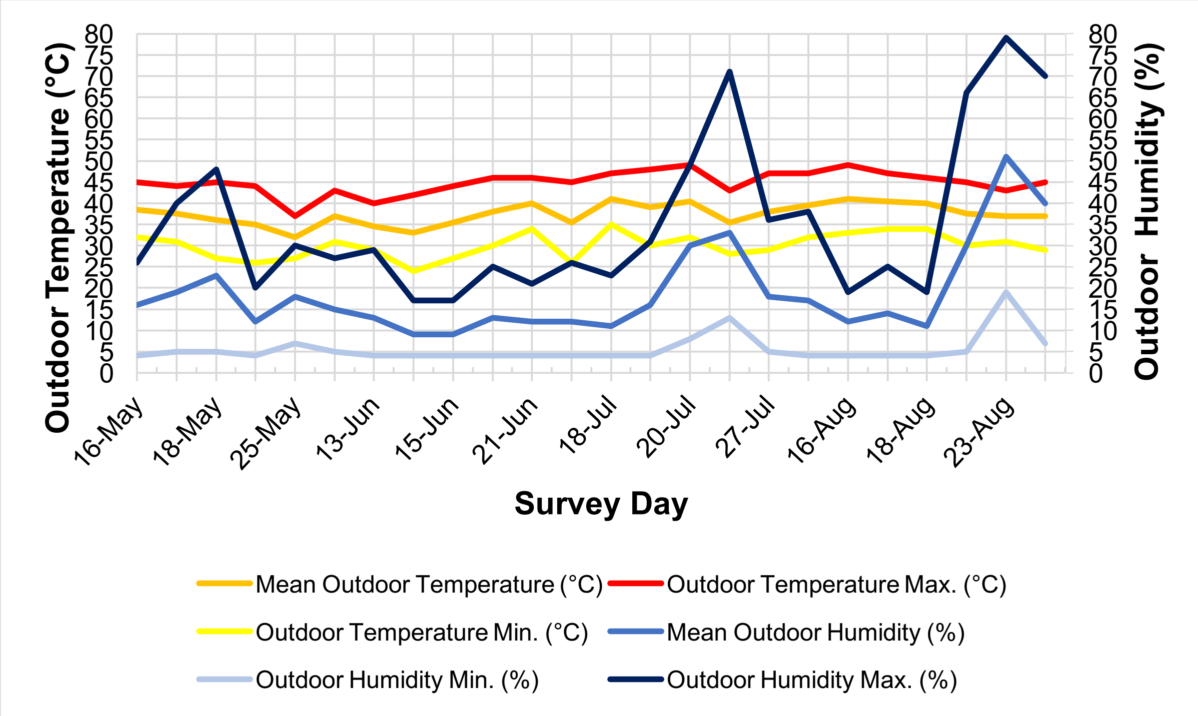


Figure 17. Chart showing the outdoor environmental data during the surveyed days. Weather data is taken from The Weather Company, LLC (2017).

During the survey days in May, the outdoor daily mean temperature varied between 32 and 38.5°C (mean= 36.1°C, SD= 2.11 °C); relative humidity varied between12 to 23% (mean= 17.2%, SD= 3.76%). In June, the outdoor daily mean temperature on the survey days varied between 33 and 40°C (mean= 35.7°C, SD= 2.33°C); relative humidity varied between 9 to 13% (mean= 11.3%, SD= 1.86%). In July, the outdoor temperature daily mean varied between 35.5 and 41°C during the survey days (mean= 39.3°C, SD= 1.73°C); relative humidity varied between 11 to 33% (mean= 20.83%, SD= 8.66%). During the survey days in August, the outdoor temperature varied between 37 and 41°C (mean= 38.8°C, SD= 1.70°C); relative humidity varied between 11 to 51% (mean= 26.3%, SD= 16.74%) as shown in Figure 17. All surveyed buildings operated in Air conditioning (AC) mode.

3.1.3 Running outdoor mean temperature (Trm)

Daily Running mean outdoor temperatures reflect the thermal experience of occupants better than the monthly mean temperatures since the outdoor mean temperature varies at a much shorter interval sometimes (Nicol, et al., 2012). Where the monthly mean temperature is taken as an average temperature of the month as a whole, but since people's responses rely heavily on their thermal experiences, the exponentially weighted mean of the running mean of the daily mean outdoor temperature is calculated from the following equation:

$$T_{rm\ (tomorrow)} = (\alpha)\ T_{rm\ (yesterday)} + (1 - \alpha)T_{odm\ (today)}$$

Where, T_{rm} is the outdoor running mean temperature and T_{odm} is the outdoor mean temperature, while α is a constant between 0 and 1 and usually is used as 0.8 (Nicol, et al., 2012). For all the survey days, the running mean temperature was estimated. It varied from 32.7 to 40.4°C and averaged at 36.7°C with Standard Deviation (SD) of 2.9°C for all four survey months.

3.2 Indoor conditions

3.2.3 Temperature and humidity

In all the surveyed buildings the indoor air temperature correlated robustly with indoor globe temperature. Absolute humidity (AH) (g_w /kg_{da}) showed a significant relationship with most of the indoor and outdoor variables. This makes humidity an important variable for thermal comfort in this area.

The buildings surveyed were all operated in AC mode, the mean indoor environmental variables varied between Private and Government buildings during the four months of survey. In private office buildings the mean indoor temperature varied between 21.6 to 26.1°C, with an average value of 23.4°C (SD=0.97°C). While in government office buildings the mean indoor temperature varied between 18.9 and 26.9°C in heavy equipment rooms. The average mean indoor temperature in government office buildings was 21.9°C (SD=1.34°C).

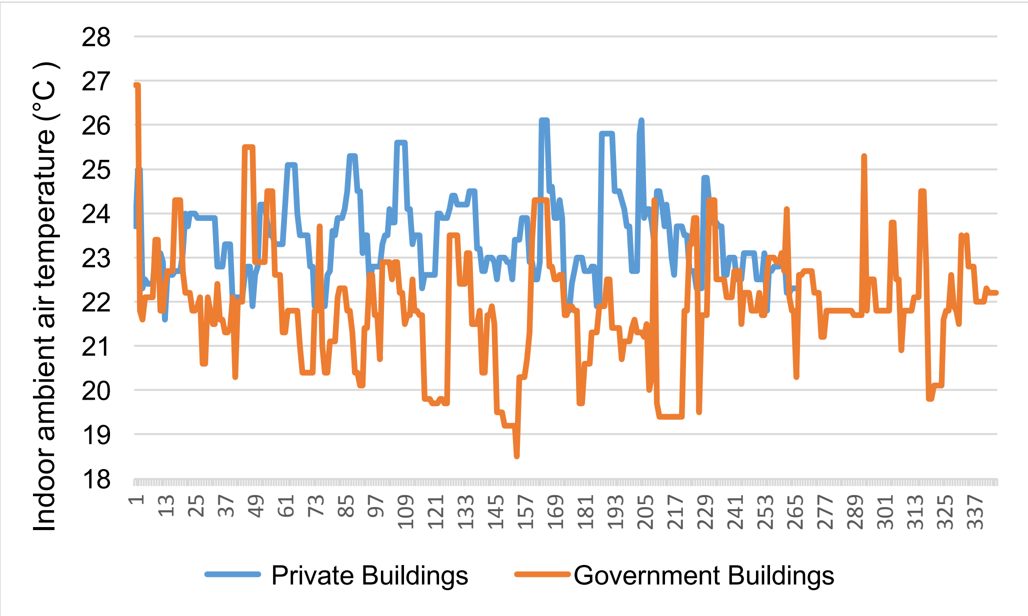


Figure 18.Chart showing indoor air temperatures (Ta) in government office buildings vs. private office buildings.

Government office buildings were measured to be at cooler temperatures than private office buildings as shown in the Figure 18. The relative humidity in private office buildings varied between 29% to 57%, and averaged at 40.1% (SD=6.3%). Slightly higher in government office buildings, the relative humidity was between 28% to 58% with an average of 41.1% (SD=5.16) for all four surveyed months.

Table 7 summarizes the relationships between the indoor and outdoor environmental variables recorded during the surveyed months. In all surveyed building indoor environments the data did not correlate with the outdoor environmental data recorded, instead it seemed to be delinked as shown in the table. This can be seen through the vast difference in temperatures between the outdoor temperature T_o and the indoor globe temperature T_g. However, in both building types the indoor air temperature strongly correlated with the indoor globe temperature. While, the mean CO_2 concentration found in the private building was 624 ppm lower than the mean CO_2 concentration in the government surveyed buildings found at 742.4 ppm.

Table 7. Recorded outdoor and indoor environmental data taken during the survey period.

Variable	Government (N=346)		Private (N=265)		All Data (N=611)	
	Mean	SD	Mean	SD	Mean	SD
T_o (°C)	**37.8**	**2.7**	**36.6**	**2.3**	**37.3**	**2.6**
RH_o (%)	**16**	**6.2**	**21**	**11.5**	**18.3**	**9.3**
T_g (°C)	**21.5**	**1.3**	**23.0**	**0.9**	**22.2**	**1.4**
T_a (°C)	**21.89**	**1.3**	**23.4**	**0.97**	**22.6**	**1.4**
RH (%)	**41.12**	**5.2**	**40.1**	**6.0**	**40.7**	**5.6**
AH (g_w/kg_{da})	**6.6**	**0.9**	**7.1**	**1.0**	**6.8**	**0.96**
Av (m/s)	**0.15**	**0.13**	**0.08**	**0.06**	**0.12**	**0.11**
$I_{cl\text{-}tot}$ (clo)	**0.835**	**0.26**	**0.701**	**0.16**	**0.777**	**0.23**
Activity (Met)	**1.15**	**0.24**	**1.21**	**0.24**	**1.2**	**0.2**
CO_2 (ppm)	**742.43**	**157.83**	**623.97**	**96.40**	**691**	**147**

N: sample size; T_o: Outdoor temperature (°C); RH_o : Outdoor relative humidity (%); T_g: Indoor globe temperature (°C); T_a : Indoor air temperature (°C); RH: Indoor relative humidity (%); AH: Indoor absolute humidity (g_w/kg_{da}); Av: Indoor air velocity (m/s); $I_{cl\text{-}tot}$: Subjects total clothing insulation (clo); Activity: Metabolic rate activity (Met); CO_2 : Indoor Carbon-di-oxide concentration (ppm).

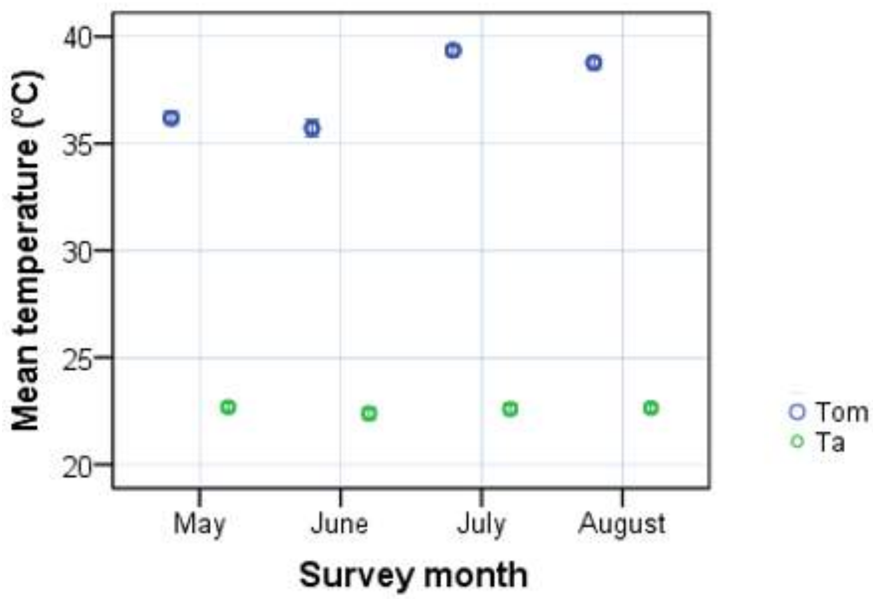


Figure 19. Error graph showing differences between outdoor and indoor mean temperatures. Error bars represent 95% confidence interval. (Where T_{om} is the outdoor mean temperature and T_a is the mean ambient indoor air temperature.)

Figure 19 error bar graph compares the indoor and outdoor mean temperatures. Immense difference is shown between the temperatures, this verifies the exaggerated overcooling of the office buildings.

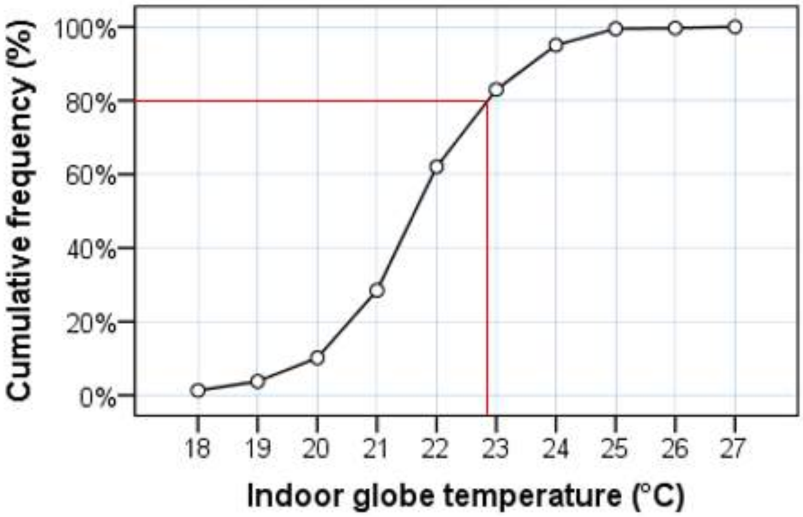


Figure 20. Indoor globe temperature cumulative frequency graph.

At 80% of the time, the prevailing indoor globe temperature of the surveyed buildings is less than 22.9 °C (Figure 19). This shows excessive cooling of the indoor environment compared to outdoor temperatures.

3.2.4 Indoor conditions: Air velocity

Indoor air speeds were primarily achieved by the AC, since fans were not available or used in any of the offices. However, open windows were found while the AC was turned on in one of the offices in B1, B3, and B4.

Air speeds varied between 0.01 to 0.69 m/s in government buildings with a median of 0.11 m/s (SD=0.13), while in private buildings it ranged from 0.01 to 0.4 m/s with a median of 0.06 m/s (SD=0.06). Interestingly, this shows that government buildings reached slightly higher indoor air speeds than private buildings. However, in both building types the air speeds recorded are considered too low for adaptation opportunities. Therefore, occupants aren't given the tools such as fans to adapt to higher indoor air temperatures. At 80% of the time (Figure 21) the prevalent air movement recorded was 0.15 m/s which is not providing enough air movement since ASHRAE suggests an air velocity between 0.18 and 0.25 m/s (ASHRAE, 2012).

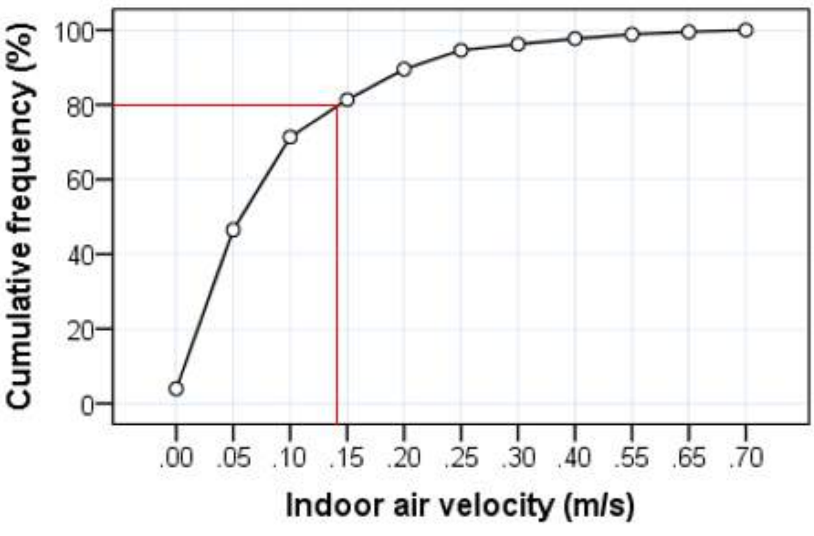


Figure 21. Indoor air velocity cumulative frequency graph.

ASHRAE recommends increased air speeds to offset the elevated air temperatures (2012). For occupants with a metabolic rate of 1.3 met or higher there is no air speed limit requirement (ASHRAE, 2013). The air speed limit requirements vary for occupants with 1.3 met or lower metabolic rates depending on the availability of occupant control of airspeed (ASHRAE, 2013). The maximum air speed limit for occupants with no controls is 1.2 m/s. Occupants with access to airspeed control have maximum air speed limits depending on T_{op}. If the T_{op} is < 22.5°C the maximum airspeed limit is 0.2 m/s, when the T_{op} is > 22.5°C the maximum airspeed limit is 0.8 m/s (ASHRAE, 2013).

The building occupants' responded to low air movements recorded by opening windows, this adaptive method was used to increase air circulation in the room. In a total survey, adaptation through opening windows was found a total of 4 times. Occupants clarified this action in that they felt "stuffy" in the office and needed to increase the air movement in the room. Higher air speeds are also known to be more effective for increasing the heat loss from the body when the mean radiant temperature is higher than the air temperature (Schiavon & Melikov, 2008).

3.3 Subjective Thermal Responses

3.3.3 Thermal Sensation (TS)

"*How do you feel in the present temperature of this room*?" the response to this direct question estimates an important psychological expression of thermal sensation relating the feeling of warmth or coolth. Figure 22 shows the distribution of thermal sensation votes. Throughout the survey a majority voted in the comfort band. It was found that 80.4% were comfortable (voting -1 to +1) in all buildings. In the LEED buildings 85% of subjects voted in the comfortable band (voting -1 to +1), while 76.3% voted comfortable in the non-LEED buildings. There were 8.3% of subjects voting on the cooler side of the scale (voting -2 and -3) in LEED buildings while 14.7% voted on the cooler scale (voting -2 and -3) in non-LEED buildings. During the month of August, more subjects were voting on the warmer end of the scale (voting +2 and +3). In contrast to the month of June where occupants voted on the cooler side of the scale (voting -2 and -3). This may have to do with the increased outdoor air temperatures and humidity levels recorded during the month of August.

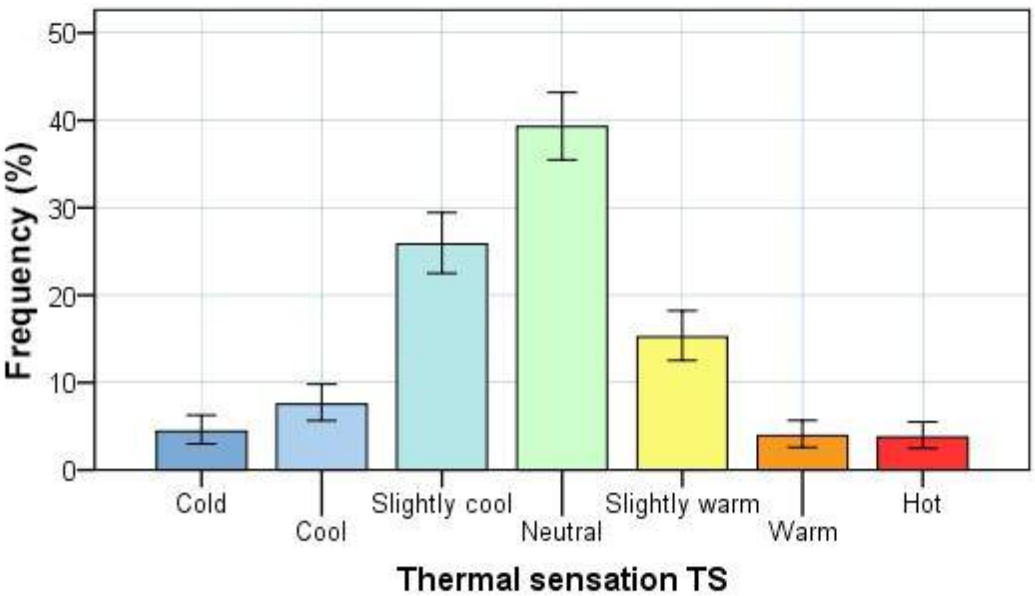


Figure 22. Occupant thermal sensation distribution for all the survey months in all buildings. Error bars represent 95% confidence interval.

3.3.4 Thermal Preference (TP)

Thermal preference was obtained through the question "how would you prefer the temperature to be in this room?" 50.8% of respondents voted no change, 11.3% voted for the preference of a warmer environment and 37.8% voted for a preference of a cooler environment. Thermal preference indicated a greater preference for cooler environments although people were voting on the cooler end of the scale on thermal sensation vote. This can be interpreted as two points: (1) as this is a summer study, people have a natural tendency to prefer a cooler sensation, and (2) there could be problems related to the semantics of the wordings of the scale when translated into Arabic. In this study, any surveyed occupant that had any confusion or questions regarding the Arabic version of the survey was given a verbal explanation regarding the scale values.

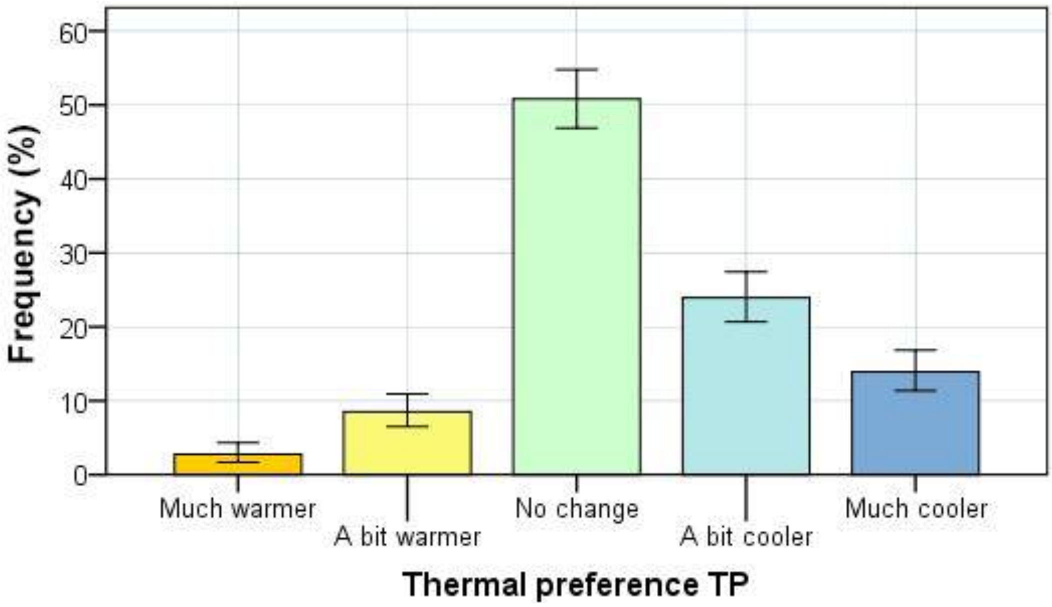


Figure 23. Thermal preference cases frequency graph.

3.3.5 Thermal acceptability (TA)

Thermal acceptability was measured as a binary input through the question "do you accept the present indoor thermal environment?" Thermal acceptability (TA) is a very complex concept that depends on several environmental, physiological and psychological variables. The most important variables to be considered are the indoor and outdoor temperatures, thermal history, expectations, and the use of environmental controls, age and gender (de Dear & Brager, 1998).

Thermal acceptability for all buildings was voted at 73.5% even though 19.6% voted outside of the three central categories of the sensation scale. Thermal acceptability varied between 86.8% in private buildings and 61.6% in government buildings. This might be due to the colder indoor environment found in government buildings, where the private buildings were kept at lower indoor air temperatures.

In the overall comfort vote (OC) 66.7% of the subjects voted comfortable. The occupants chose one of the first three categories (voting 1, 2, and 3) on all the data, translated as (very comfortable, moderately comfortable, and slightly comfortable). 87.2% of the subjects voted comfortable in the first three categories (voting, 1, 2 and 3) in LEED buildings. In non-LEED buildings where lower indoor air temperatures were maintained 50.7% voted comfortable.

3.4 Effect of clothing

Clothing was found to be one of the most important and immediate adaptation methods available to the subjects. Some adapted to the cooler indoor temperatures by using jackets and shawls. Other forms of adaptation through clothing were also recorded. Subjects were found to be rolling up their sleeves and taking off their "gitra" or suit jacket in response to the warmer indoor temperatures.

No strict dress code was observed in any of the offices. Both male and female clothing ensembles varied from western to non-western and casual to chic wear. Adaptation through clothing greatly influenced the subjects' clo values in relationship to the indoor mean radiant temperatures T_{mr}.

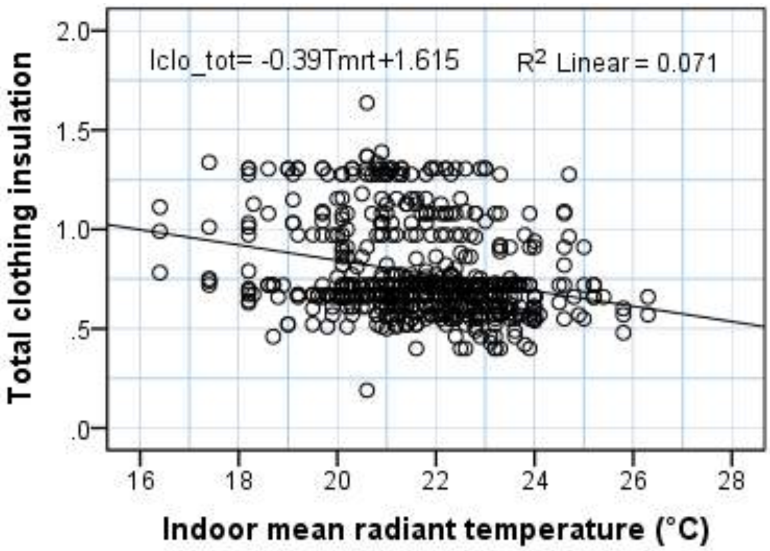


Figure 24. Linear regression between indoor mean radiant temperature and total clothing insulation.

Strong correlation was found between the total clothing insulation (I_{clo_tot}) and the Indoor mean radiant temperature (T_{mrt}) in Figure 24. The regression line shows that as the indoor mean radiant temperature increases the clo values decrease. As subjects wore ensembles they reduced layers of clothing adaptively as the indoor temperature rose. Through regression analysis the following I_{clo_tot} equation was found:

$$I_{clo\_tot} = -0.39T_{mr} + 1.615 \qquad (r= 0.267, SE= 0.006, p< 0.001)$$

3.5 Self-declared productivity

Self-declared productivity was found by asking the question "how is your productivity now as affected by the room environment?" It became evident that, as the thermal environment became acceptable, the productivity was higher (Figure 25).

Thermal sensation and overall comfort also strongly correlated with productivity. Subjects that did not accept their thermal environment conditions were not able to be productive to their normal potential. About 99% of people who stated their productivity "much lower than normal" were "unsatisfied" with their thermal environment shown as the red bar in Figure 25. Occupants that were satisfied with their thermal environments were voting "normal", "slightly higher than normal" and "much higher than normal" in the self-declared productivity vote shown in the bars colored in shades of green.

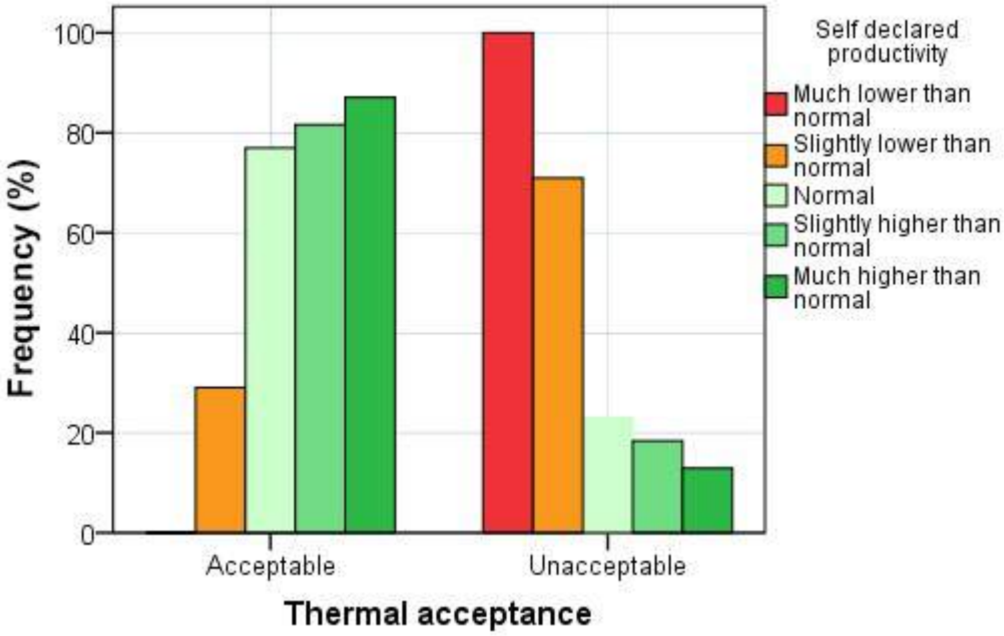


Figure 25. Frequency of cases in Occupant thermal acceptability and productivity.

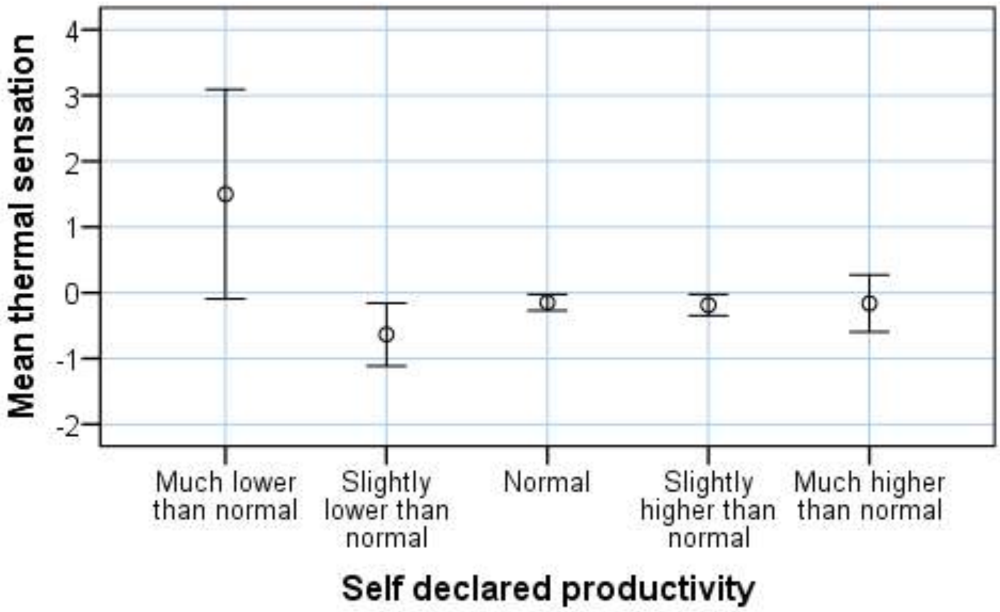


Figure 26. Mean thermal sensation scale votes in correspondence to subjects' productivity. Error bars represent 95% confidence interval.

Figure 26 shows the robust relationship between thermal sensation votes and self-declared productivity. As the thermal sensation is closer to 0 meaning "neutral" the self-declared productivity is higher. Neutral thermal sensation is when the subjects are feeling neither too hot nor too cold.

Figure 27. Mean overall comfort scale in correspondence to subjects' self-declared productivity. Error bars represent 95% confidence interval.

Subject's self-declared productivity improved as their overall comfort perception improved as seen in Figure 27.

3.6 Fanger's Predicted Mean Vote (PMV)

PMV was estimated for all the datasets using the ASHRAE'S comfort calculator (ASHRAE, 2012), using all the environmental and personal parametric inputs. PMV was then regressed with the indoor globe temperature T_g (°C) and the results were plotted alongside the regressed line of the thermal sensation (Figure 28).

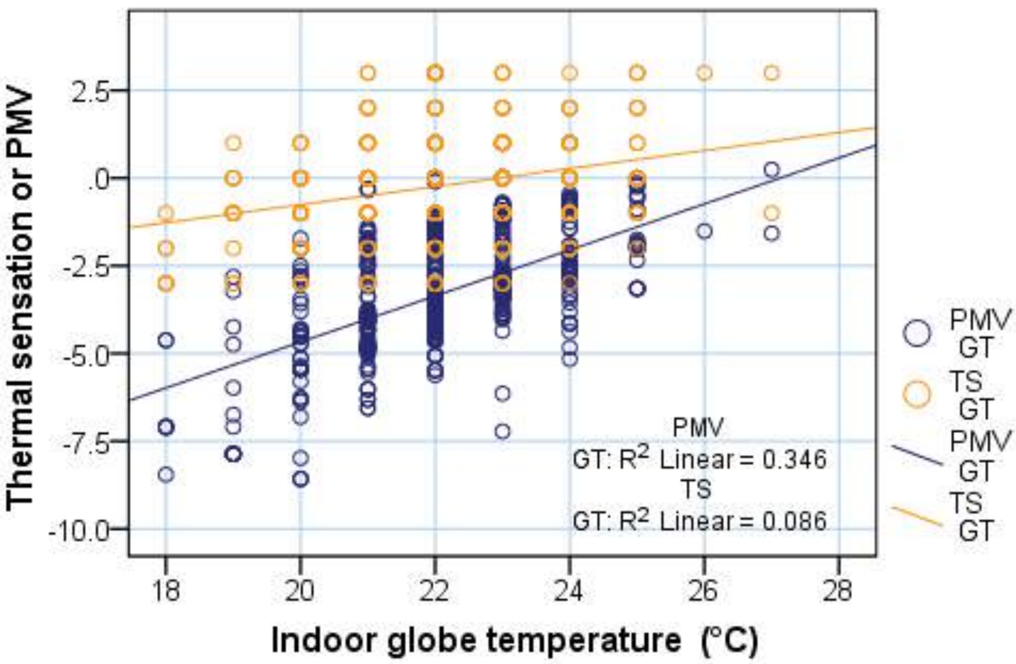


Figure 28. Thermal sensation and PMV regressed with the Indoor globe temperature.

PMV being a heat balance model, is under-predicting at lower temperatures a lot more. It does not take all the adaptation of occupants into consideration. The PMV accounts for clothing, metabolic rate and air velocity modifications only to some extent. PMV was found to be always significantly over predicting the actual thermal sensation of respondents in all temperature ranges as shown in Figure 27 where people are always voting to be warmer than what the PMV predicts. This is clearly evident through the distribution of the recorded comfort vote and PMV in reference to the indoor globe temperature. This was found through the equations:

$$PMV = 0.656T_g - 17.786 \qquad (SE= 0.037,\ r= 0.588,\ p<0.001)$$
$$TS = 0.257T_g - 5.901 \qquad (SE= 0.034,\ r=0.294,\ p<0.001)$$

In addition, the PMV model considers clothing as a passive insulation around the body, but in many climates and cultures clothing is used in more dynamic ways to alter the microclimate around the skin (Indraganti, et al., 2013). As suggested by Nicol and Humphreys (2004), PMV is a model that represents thermal equilibrium as a heat balance "at a point in time" that cannot fully explain the temporal conditions the occupants experience in reality.

Not only does the PMV model ignore many behavioral changes but it also ignores respondents' different methods of adaptation in the thermal environments as well. This includes the adaptation through environmental variables such as opening doors and windows and the adaptation through clothing by using layering in some cases. The cumulative effect of these minor sources of error led to the gross deviation of the PMV from the actual sensation. Since the PMV is a static heat balance model it has failed to explicate this.

The data in this research supports the conclusive demonstration of Nicol and Humphreys (2004) that the errors in PMV are not just confined to the naturally ventilated buildings alone, but are masked by the narrow range of temperatures experienced in AC buildings as well. In addition, this finding questions the straightforward application of PMV in the design of indoor temperatures in air-conditioned spaces.

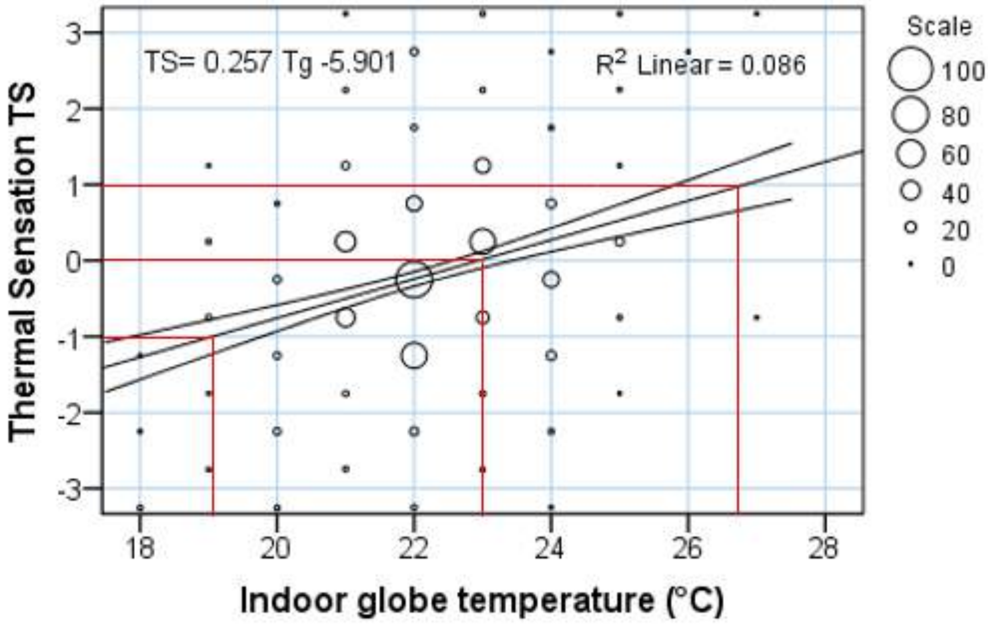
3.7 Comfort temperature

3.7.3 Linear regression analysis

Research points out that the PMV model does not fully explain the indoor conditions experienced even in air-conditioned buildings. It may be that the discrepancies are masked by the narrow range of conditions (Humphreys & Nicol, 2002). Therefore, it is important to search for an adaptive relationship that can better explain the situation in real-life buildings. Hence the search for an adaptive relationship in AC buildings as shown in the following sections.

The comfort temperature is one of the major outcomes of a thermal comfort field study data analysis. While some data can be fit into a regression line to yield a reliable comfort equation, many times this may not be possible. Several reasons ranging from adaptation to limited change in thermal environments may be the causative factors.

The Griffith's temperature and/or globe temperature recorded when the subjects voted neutral also gives reliable information on the comfort temperature, each with its own advantages and limitations. Figure 29 shows the regression line of the thermal sensation votes with the indoor globe temperatures. Where the lines in red at thermal sensation votes (0, 1, -1) indicate the comfort zone for the respondents in accordance to their votes. Where "1" is the upper limit, "0" is the neutral limit, and "-1" is the lower limit.



P<0.001; the outer lines represent 95% confidence interval of the slope of the regression line.

Figure 29. Relationship between indoor globe temperature and thermal sensation.

3.7.4 Estimation of Griffith's comfort temperature and the adaptive model

Griffith's method (1990) is widely used in the comfort data analysis. In this method an increase of 3K in temperature for each scale point on the thermal sensation scale is assumed (Rijal, et al., 2015). Therefore, for each thermal sensation scale vote away from neutral, a 3K in temperature was added or subtracted from the actual temperature when measured to acquire the expected temperature that results in neutrality (Rijal, et al., 2015). This assumption was unequivocally validated through numerous climate chamber studies. Many researchers employed Griffiths' method in their comfort temperature predictions (McCartney & Nicol, 2002) (Indraganti, et al., 2013).

Griffiths' comfort temperature (T_{comf}) was estimated using the equation:

$$T_{comf} = T_g + (0-TS) / G$$

Where, T_{comf} is the Griffith's comfort temperature, T_g is the indoor globe temperature, TS is the sensation vote, and G is the Griffiths slope taken as 0.33 K^{-1} (indicative of a 3 K rise for unit perturbation in sensation vote).

Griffiths' comfort temperature was estimated for all the comfort votes. The mean T_{comf} obtained was 22.5 °C. This value matched closely with the regression comfort temperature obtained through the linear regression of globe temperature with the thermal sensation and the actual globe temperature recorded when voting neutral as shown in Figure 30.

3.8 Comparison with the adaptive models in CIBSE guide and ASHRAE standard

The data has been superimposed on the adaptive model shown in CIBSE guide as shown in Figure 30. Overcooling of the office buildings is shown in the CIBSE standard graph where T_{comf} is revealed for many to be at a higher temperature range. This is shown by the points in the graph representing individual votes, the occupants are shown to be comfortable at higher range of indoor temperature. This articulates that people have the acceptance to adapt to higher indoor temperatures given a chance. In addition, the graph displays that the CIBSE guide was not designed for the hot climate of Kuwait and the Middle East. It was developed and intended for a much cooler environments. This is presented where all the votes are taken when the outdoor mean temperatures are higher than 33°C and go up to +40°C. These higher outdoor temperature ranges are not covered in the CIBSE guide as can be seen in Figure 30.

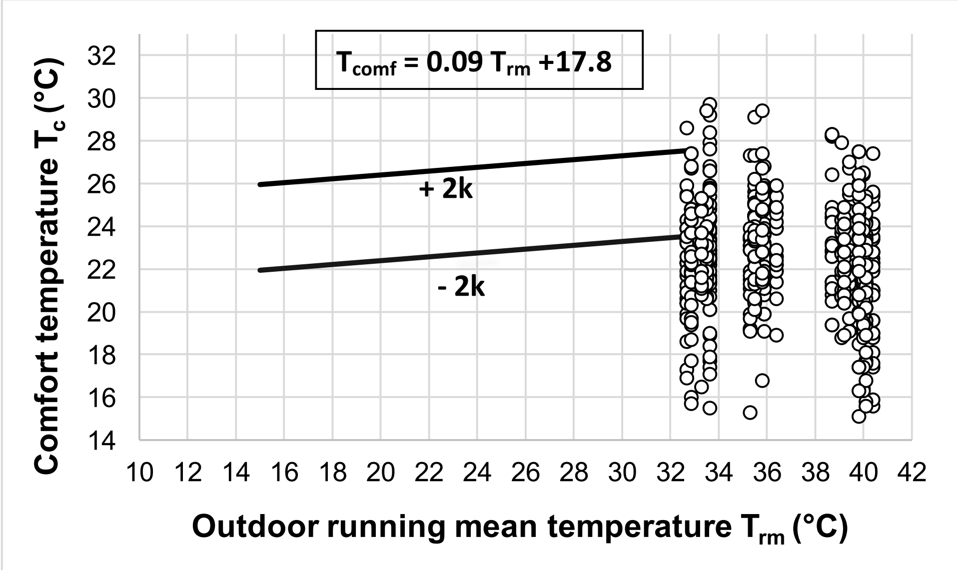


Figure 30. Relationship of the Griffiths' indoor comfort temperature with the running mean outdoor temperature super-imposed over the CIBSE standard (Each point represents a single vote.)

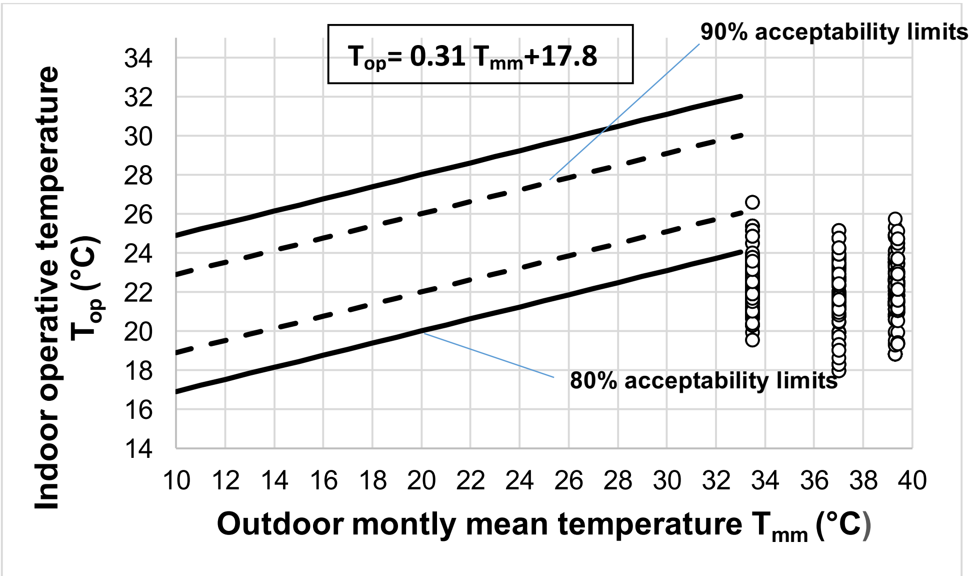


Figure 31. Relationship of the operative temperature with the monthly mean temperature super-imposed over the ASHRAE standard (Each point represents a single vote.)

The upper limit +/- 4K shows 80% acceptability, where the lower limit +/-2K shows 90% acceptability on the ASHRAE standard.

Since both the ASHRAE standard and the CIBSE guide are developed for much cooler climates, a new custom made standard should be developed targeting the climate of Kuwait.

3.9 Adaptation mechanisms observed

Occupants had to deal with a wide range of issues ranging from cold and warm discomfort to poor quality lighting. Subjects adapted through layering of clothing to avoid the cold discomfort.

Although, windows were provided with the venetian blinds and roll up screens, their use was limited in larger office settings. Windows were sometimes used to warm the office as well. When windows are operable, occupants opened the window to increase air circulation in the "stuffy" offices as the occupants articulated as well as to warm the overcooled offices. This would lead to energy wastage, creating unnecessary increase in CO_2 emissions and adding more harm to our environment.

Figure 32. Occupants opening windows in overcooled offices to bring in warmth from the hot outdoors. It was also noted that some occupants opened windows to increase ventilation.

Behavioral adaptation was found throughout the offices. Subjects adapted through various means behaviorally. The use of shawls, scarfs and light jackets to adjust to cool indoor temperatures were some of the most common methods of behavioral adaptation found in both genders. Resting during the day, eating and drinking hot beverages was also noted during the field surveys. When it got too warm for occupants' preference, subtracting layers of clothing and changing the hair styles (ex. tying hair in back in a ponytail) was the most common way of adaptation noted.

3.10 Conclusions

The maximum daily outdoor temperatures on the surveyed days were found to be between 38°C and 51°C with a mean temperature of 43°C.

The clothing insulation varied from 0.400 to 1.637 clo. Outdoor conditions varied during the survey with oscillation in temperature in June and July and escalation in humidity were noted during the end of August. The indoor thermal conditions were significantly delinked from the outdoors. Following are the conclusions:

1. The comfort temperature of 22.5 °C was obtained. This matched closely with the Griffith's comfort temperature and the globe temperature recorded when the subjects voted neutral on the sensation scale. Building occupants are overly accustomed to the use of excessive air conditioning and have shown their ability to adapt to cooler indoor office temperatures. This shows a high dependency on air conditioning and over cooling buildings to the point of energy wastage and depletion. By providing more adaptive opportunities in buildings (such as environmental controls like fans and methods to increase air movement and circulation) occupants will be able to adapt to a higher range of indoor temperatures. This will provide higher comfort temperatures that occupants can

adjust to making it more economic and environmentally realistic to sustain for our climate type.

2. 80.4% of subjects voted comfortable on the sensation scale. The offices are excessively overcooled which does not give a chance for people to show different adaptation methods for a wider variety of temperature bands. People are getting accustomed to their “comfort zone” in overcooled buildings and not their “otherwise possible comfort zone” in their region’s climate. This is causing a significant delink between indoor and outdoor environments. This is not a viable solution and it leads to severe waste of energy, money and thermal monotony.
3. The indoor air speed observed was much slower than the standard maximum recommended speed for summer. This leaves scope for raising the comfort temperature in future buildings by using higher indoor air speeds. These can be controlled by the occupants, though the use of high efficacy fans.
4. By not providing creative design solutions with tools for adaptation, we are creating buildings that lack any identity or regional character and diversity. Buildings should be designed to cater to the region’s climate and human adaptation through low energy means. For example, window design and coverage area, building material selection, and indoor adaptive possibilities should all be a crucial part of the initial design stage to enhance our built environment and opportunities.
5. PMV significantly underestimated the actual sensation always. People are always voting to be warmer than what the PMV predicts.
6. The extremely high temperatures of the Middle Eastern climate are outside the applicability ranges specified in the ASHRAE standard and CIBSE guide. This shows when the graph was regressed on the adaptive models, the higher temperatures in the region are not included as part of the model. An adaptive model specific to Kuwait’s climate may well be developed.
7. Subjects adapted through clothing and environmental controls which were available to them.
8. The LEED building missed the opportunity to include operable windows overlooking the central courtyard. This would have helped people use the windows as an adaptation method. The micro-climate created in the courtyard by the vegetation and water would have cooled the offices overlooking it in the early mornings and late afternoons and cut the energy consumption during that period.
9. This study calls for extensive future research in various buildings with more people to further elucidate the adaptation and to develop a new adaptive model specific to Kuwait and similar climates. It also questions the relevance of straight forward application of PMV, more so when the energy concerns are more pertinent than ever.
10. We used a translated version of the ASHRAE thermal sensation scale supplemented with the surveyor’s verbal interpretation when needed. However, it may be better to develop and test a complete suite of thermal scales in Arabic for large-scale surveys later. All the researchers in the Middle Eastern region can then use the Arabic scales uniformly, eliminating the need for surveyor’s interpretation.

References

Al-ajmi, F., 2010. Thermal comfort in air-conditioned mosques in the dry desert climate. *Building and Environment,* 45(11), pp. 2407-2413.

Al-ajmi, F. & Loveday, D., 2010. Indoor thermal conditions and thermal comfort in air-conditioned domestic buildings in the dry-desert climate of Kuwait. *Building and Environment,* 45(3), pp. 704-710.

Al-ajmi, F., Loveday, D., Bedwell, K. & Havenith, G., 2008. Thermal insulation and clothing area factors of typical Arabian Gulf clothing ensembles for males and females: Measurements using thermal manikins. *Applied Ergonomics,* Volume 39, p. 407–414.

Al-Rashidi, K. & Loveday, D. A.-M. N., 2009. Investigating the applicability of different thermal comfort models in Kuwait classrooms operated in hybrid air-conditioning mode. *Sustainability in energy and buildings,* pp. 347-355.

ASHRAE, 2012. ANSI/ASHRAE Addendum d to ANSI/ASHRAE Standard 55-2010. *Thermal Environmental Conditions for Human Occupancy.*

ASHRAE, 2013. Thermal Environmental Conditions for Human Occupancy. *ANSI/ASHRAE Addendum b to ANSI/ASHRAE Standard 55-2013.*

Budaiwi, I. M., Abdou, A. A. & Al-Homoud, M. S., 2013. Envelope retrofit and air-conditioning operational strategies for reduced energy consumption in mosques in hot climates. *Building Simulation ,* Volume 6, pp. 33-50.

de Dear, R. & Brager, G., 1998. Developing an adaptive model of thermal comfort and preference. *ASHRAE Trans,* 104(1), pp. 145-167.

dreamstime, 2017. [Online] Available at: https://pt.dreamstime.com/ilustra%C3%A7%C3%A3o-stock-povos-tradicionais-da-roupa-de-ar%C3%A1bia-saudita-image71084812

fotolia, 2017. *Adobe stock.* [Online] Available at: https://www.fotolia.com/id/89352404

freepik, 2017. [Online] Available at: http://www.freepik.com/free-photos-vectors/clothing

Googlemaps, 2016. [Online] Available at: https://en.wikipedia.org/wiki/Kuwait

Googlemaps, 2016. *Google Maps.* [Online] Available at: https://www.google.com.kw/maps/place/Kuwait+University+Khaldiya+Campus/@29.3216128,47.9704888,243m/data=!3m1!1e3!4m5!3m4!1s0x3fcf9b1073a43367:0x7fbaa47b0d21a3a7!8m2!3d29.3217476!4d47.9719305?hl=en

Googlemaps, 2017. *Google Maps.* [Online] Available at: https://www.google.com.kw/maps/@29.3579997,47.9073713,408m/data=!3m1!1e3?hl=en

Griffiths, I., 1990. *Thermal comfort in buildings with passive solar features: field studies,* UK: Report to the Commission of the European Communities.

IEA, 2017. *IEA.* [Online] Available at: http://www.iea.org/weo2017/

Indraganti, M., Ooka, R. & Rijal, H., 2013. Field investigation of comfort temperature in Indian office buildings: A case of Chennai and Hyderabad. *Building and Environment,* Volume 65, pp. 195-214.

Indraganti, M., Ooka, R. & Rijal, H. B., 2013. Thermal comfort in offices in summer: Findings from a field study under the 'setsuden' conditions in Tokyo, Japan. *Building and Environment,* Volume 61, pp. 114-132.

Kempton, W., Feuermann, D. & McGarity, A. E., 1992. "I always turn it on super": user decisions about when and how to operate room air conditioners. *Energy and Buildings,* 18(3), pp. 177-191.

McCartney, J. & Nicol, J., 2002. Developing an adaptive control algorithm for Europe. *Energy Buildings,* Volume 34, pp. 35-623.

Nicol, F., Humphreys, M. & Roaf, S., 2012. *Adaptive thermal comfort: principles and practice.* s.l.:Routledge.

Nicol, J. & M, H., 2004. A stochastic approach to thermal comfort- occupant behaviour and energy use in buildings. *ASHRAE Trans,* pp. 68-554.

NRDC, 2017. *NRDC.* [Online] Available at: https://www.nrdc.org/stories/global-warming-101

Parsons, K. C., 1994. Thermal comfort standards: past, present and future. In: *Thermal Comfort: Past, present and future.* Garston, United Kingdom: BRE, pp. 184-197.

pinterest, 2017. *Pinterest.* [Online] Available at: https://www.pinterest.com/pin/492862752953936947/

Rijal, H. B., Humphreys, M. & Nicol, F., 2015. Adaptive thermal comfort in Japanese houses during the summer season: behavioral adaptation and the effect of humidity. *Buildings,* pp. 1037-1054.

Schiavon, S. & Melikov, A., 2008. Energy savings and improved comfort by increased air movement. *Energy Buildings,* Volume 40, pp. 60-1954.

USGBC, 2015. *US Green Building Council.* [Online] Available at: http://www.usgbc.org/leed

worldpopulationreview, 2017. [Online] Available at: http://worldpopulationreview.com/countries/kuwait-population/

Wunderground, 2017. *Wunderground.* [Online] Available at: https://www.wunderground.com/global/stations/40582.html

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Temperature analysis and the effect of urban development on the outdoor thermal comfort and intensification of the Urban Heat Island phenomenon in the United Arab Emirates

Evangelia Topriska[1], Hassam Nasarullah Chaudhry[1], Mehdi Nazarinia[2]

[1] Heriot-Watt University Dubai, School of Energy, Geoscience, Infrastructure and Society, Architectural Engineering Department, Dubai International Academic City, Dubai, UAE, P.O.Box: 294345; e.topriska@hw.ac.uk
[2] Heriot-Watt University Dubai, School of Engineering and Physical Sciences, Mechanical Engineering Department, Dubai International Academic City, Dubai, UAE, P.O.Box: 294345

Abstract: This paper presents the temperature distribution and identification of Urban Heat Island intensity and outdoor thermal comfort conditions in a residential cluster in Dubai, UAE. Temperature and humidity data are collected during peak summer period and thermal imaging is further used as additional tool. From the analysis it is reported that the maximum temperature recorded in the cluster is 55 °C and the minimum is 22.9 ° C. The hottest day has an average temperature of 40.5 °C and the coolest day an average temperature of 36.1 °C. The highest temperatures during each day occur between 10am and 3pm and relative humidity peaks to 100% during night hours. The outdoor comfort is evaluated as a combination of the high temperatures and the relative humidity, and extreme discomfort is identified. Further analysis in the residential cluster, identified "hot spots" in specific areas where the spacing between the buildings is minimized. The temperature difference between these spots and other locations in the residential cluster can reach a maximum of about 12%. The temperature patterns in the cluster are also analysed with the use of CFD modelling and the results highlight the relation between the ventilation paths and the increased temperatures.

Keywords: Outdoor Thermal Comfort; Urban Heat Island; United Arab Emirates; Temperature Distribution

1. Introduction

Today's rapid urban development has led to a large increase of building energy use and subsequently fuel use and Greenhouse Gas emissions. Particularly in urban locations, the increase in energy related combustion and emissions, in combination with the specificities of the structural planning and materials used for construction, has had an increasing effect on heat concentration and ambient temperatures. This is the phenomenon described by scientists as Urban Heat Island (UHI) (Kolokotroni & Giridharan, 2008; Levermore, Parkinson, Lee, Laycock, & Lindley, 2017; Hassid, et al., 1999).

The United Arab Emirates is a country which during the last 40 years has experienced rapid growth and development, and statistics show that energy use has increased by more than 100% (The World Bank, 2014). The monthly average ambient temperatures have also experienced an increase of approximately 4 °C during the past 100 years (The World Bank, 2017). Due to this phenomenon, the increase in building's energy use due to the cooling systems has been significant, and it has been reported that almost 80% of the building energy use is for air conditioning (Indraganti & Boussaa, 2017).

Dubai in particular, is one of the 7 emirates that has experienced the most extreme development in the past 30 years. As an effect, the ambient environment has changed radically, leading thus to the observation of higher external temperatures in the city. (Taleb & Abu-Hijleh, 2013). Many researchers have focused on the impact of the increased external temperatures on the regional building energy use and thermal comfort (Brumana, Franchini, & Perdichizzi, 2017; Al-Sallal & Al-Rais, 2011). Outdoor thermal comfort in an exponentially advancing nation like the United Arab Emirates plays a major role in the growth of its economy and the satisfaction of its citizens. Furthermore, for external work environments, industries like construction, process and manufacturing, outdoor thermal comfort is a necessary aspect to be considered. Poor outdoor thermal comfort forces people to stay indoors and thereby increases the consumption of energy in buildings through air conditioning of interior spaces. Consequently, this energy produced generates greenhouse gases, which cause warming of outdoor air, contributing to higher outdoor air temperatures.

This paper presents a study of the temperature distribution in a residential cluster in urban Dubai. Data of air temperature and relative humidity are collected over a 3-week period during peak summer. The temperature distribution in the cluster is analyzed to identify the UHI intensity and highlight the parts where the heat intensity is higher. The analysis further deals with the outdoor comfort conditions of the cluster as a result of the harsh summer weather conditions. Moreover, through Computational Fluid Dynamics (CFD) analysis using ANSYS Fluent V17.2 software, the temperature and wind path and velocity in the cluster and their effect on the outdoor thermal comfort are discussed.

2. Methodology

2.1 Experimental Methodology

This paper evaluates the temperature distribution at a local microscale level in the residential compound of "The Sustainable City (TSC)" which is located southeast of the Dubai city center, as shown in Figure 1. The vision of TSC mainly encompasses the three pillars of sustainability: environmental, economic and social. According to the developers, the city's master plan is technically very thorough, exceeding the best practices in environmental building technologies and innovative architectural typologies (Diamond Developers, 2017). The microclimate study conducted in this work seeks to identify and understand the formation of the temperature intensity and local hot spots created by the building topology in a selected building cluster within the The Sustainable City and how this affects the outdoor thermal comfort of the occupants.

The first part of the assessment is based on measured data and evaluates the distribution of the temperature and humidity within the cluster. The buildings have a "desert sand" color and are built in close proximity to some local vegetation of dessert bushes and palm trees used as a separation between the clusters. Furthermore, temperature records from the Al Maktum International airport (DWC) weather station, which is located in a suburban area approximately 60 km from the city center, were collected (Dubai World Central (DWC), 2017; Weather Underground, 2017). The airport data are used as a reference base for comparison with the measured data to establish the UHI intensity.

The 3-week experimental period spread from the 28th of May till the 11th of June 2017. All measurements were taken during sunny days with clear sky conditions. The original points of measurements used for the analysis of this paper are shown in Figure 2. Readings were taken with an interval of 5 minutes at each point. The readings included maximum, minimum and average temperature and maximum, minimum and average relative humidity. The readings were taken at points of approximately 2m height from the ground. The equipment used for the data collection is presented in Table 1.

Table 1. Experimental equipment used for data collection, source: (Gemini data loggers, 2017; Flir, 2017)

Equipment	Range
Tiny Tag View 2 TV 4500	Temperature : -25 °C to +70 °C with resolution of 0.02 °C
	Relative humidity 0 to 100% with resolution of 0.3%
Flir C2 thermal camera	-10 °C to +150 °C with accuracy of 2%.

Figure 1.The Sustainable City location in the Dubai emirate

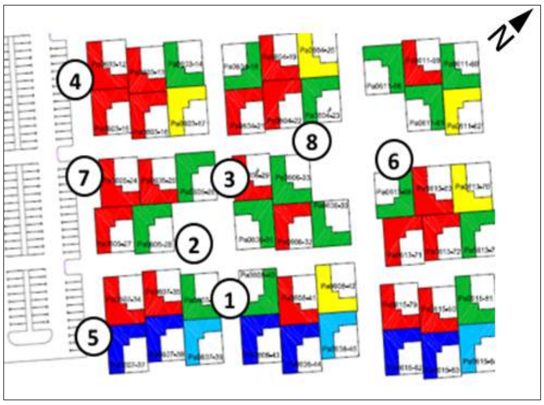


Figure 2. The position of the data loggers within the cluster

2.2 Numerical Methodology

Computational Fluid Dynamics (CFD) was further used as a tool to evaluate the temperature distribution and air paths and velocity in The Sustainable City cluster. The cluster model was developed and the flow around it was solved in ANSYS Fluent V17.2 software. The model was validated against the experimental data and the error was found to be approximately 8%. Thus it was proved to be a reliable tool to evaluate the effect of the UHI intensity on the cluster and the outdoor thermal comfort as a result of the cluster building topology and design, as well as a future guide for mitigation strategies.

The Dubai International Airport (DXB) wind data was used to determine the dominant wind speed and direction. The dominant wind speed and direction are 3.71 m/s and 220˚ and they were used in the present numerical simulation boundary conditions. The computational domain included residential cluster which was modelled as per the actual specifications. A tetrahedron meshing technique was applied on the geometry wherein the boundary conditions were applied on the edges and faces. The total mesh size comprised of 753,506 cells, 232,961 nodes, and 1,674,584 faces. The applied steady state boundary conditions included a reference velocity of 3.71m/s at a height of 1.7m. Direct solar radiation at the local coordinates was calculated by the software as 1423 W/m^2 and the diffuse solar radiation was 200 W/m^2. Different ambient temperatures were selected ranging from 30 °C to 45 ˚C.

3. Data on the temperature and humidity distribution

Overall for the cluster, it is observed in Figure 3 that during the data collection period a temperature variation exists. The hottest day is the 7th of June with an average daily measured temperature of 40.50 °C and the coolest day the 4th of June with average daily measured temperature of 36.08 °C.

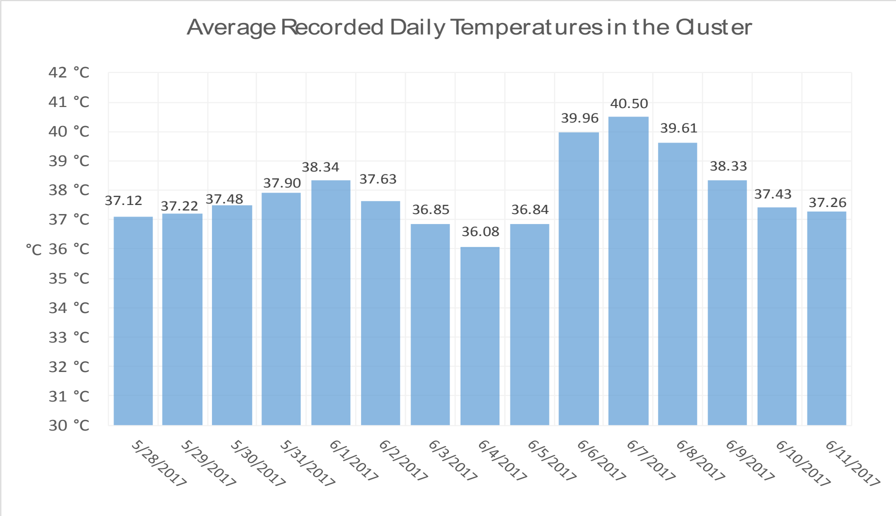


Figure 3. Average recorded daily temperatures in the cluster

Overall for the experimental period, the measured air temperature is higher than 30 °C for 75% of the time, as presented in Table 2.

Table 2. hours and percentages of temperatures above 30°C

Date	Total Hours above 30 °C	Night hours (9pm-6am)	Day hours (6am-9pm)	Night percentage	Day percentage
28-May	15.8	3.00	12.75	19.0%	81.0%
29-May	16.0	3.42	12.58	21.4%	78.6%
30-May	15.4	3.00	12.42	19.5%	80.5%
31-May	15.7	3.08	12.58	19.7%	80.3%
1-Jun	15.8	3.00	12.75	19.0%	81.0%
2-Jun	16.8	4.00	12.83	23.8%	76.2%
3-Jun	18.0	4.92	13.08	27.3%	72.7%
4-Jun	18.1	4.75	13.33	26.3%	73.7%
5-Jun	16.0	3.25	12.75	20.3%	79.7%
6-Jun	20.7	6.83	13.83	33.1%	66.9%
7-Jun	21.9	7.50	14.42	34.2%	65.8%
8-Jun	23.8	8.92	14.92	37.4%	62.6%
9-Jun	21.0	7.33	13.67	34.9%	65.1%
10-Jun	18.2	5.00	13.17	27.5%	72.5%

Figures 4 and 5 present the measured temperature and humidity data for each location in the cluster. As it is observed the different locations within the cluster present different temperature and humidity profiles. The minimum recorded temperature point in the cluster is 22.90 °C and the maximum recorded point is 55 °C. The maximum recorded temperatures on average in the cluster is 49.40 °C on the 6th June at 3pm. The minimum recorded temperature on average in the cluster is 25.13 °C on the 28th May at 5.40am.

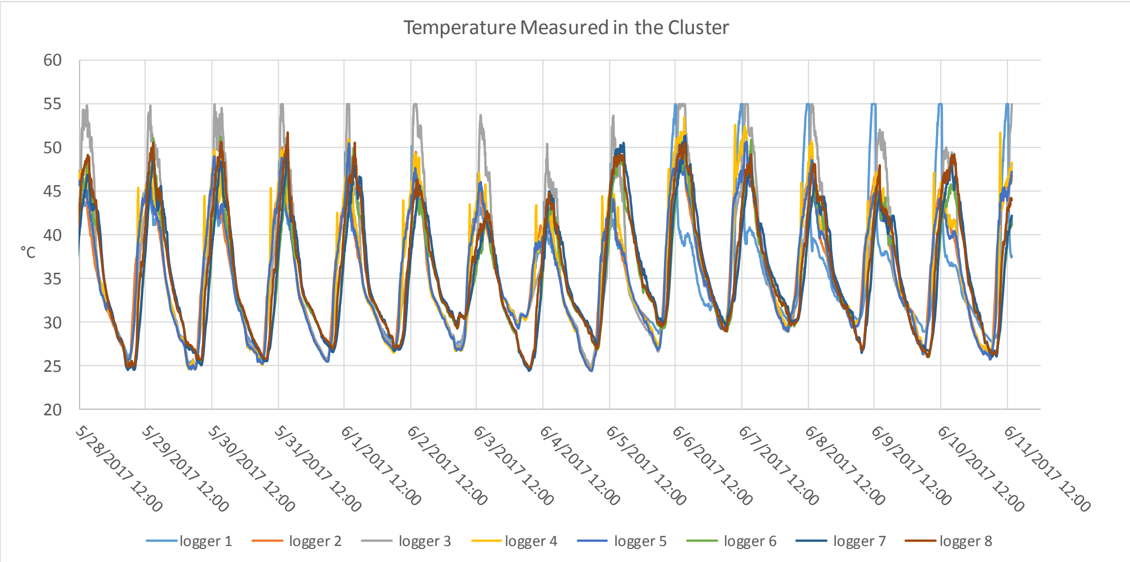


Figure 4. Temperature measured in the cluster

The minimum recorded relative humidity point in the cluster is 7.28% and the maximum is 100%. Overall it can be observed that the relative humidity presents the highest values until June the 3rd and then drops to peaks of around 70%. The maximum recorded on average in the cluster is 97% on the 2nd June at 6am. The minimum recorded humidity on average in the cluster is 12% on the 7th June at 3.20pm.

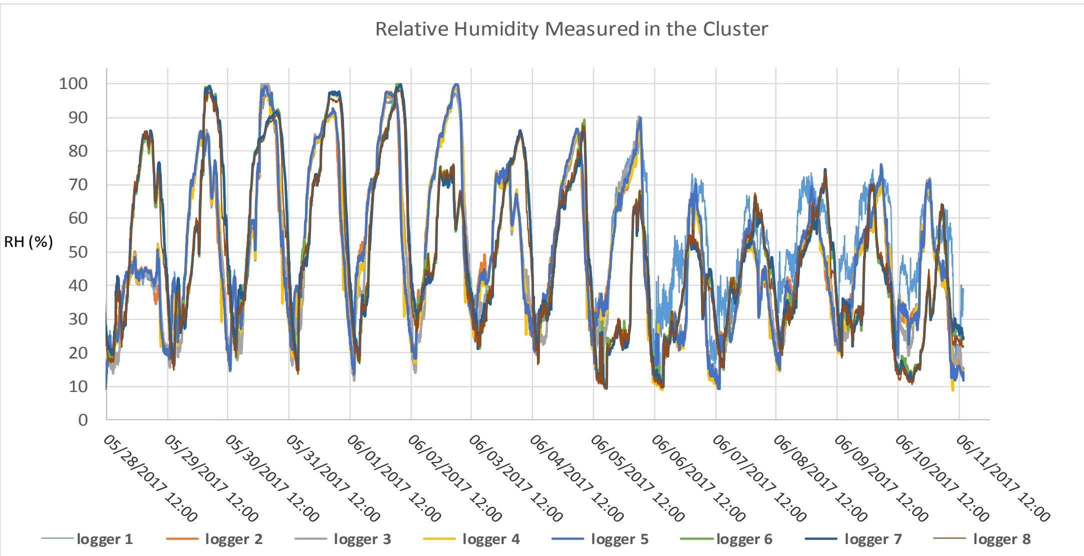


Figure 5. Relative humidity measured in the cluster

4. Analysis of the on the temperature and humidity distribution

For the duration of the experimental measurements, the hottest spot in the cluster is identified to be the logger 3 position with an average maximum temperature of 53.90 °C. The temperature recorded at the position of logger 3 does not drop below 24.50 °C for the whole experimental period and the maximum recorded temperature is 55 °C and this is reached for 10 days out of the 15.

The logger that presents the highest average relative humidity is that of position 1, with an average value of 53.90%. However, logger 3 presents the most relative humidity peaks of 100%. In the location of logger 3 both temperature and relative humidity peak more than in the other cluster locations. The average mean and maximum temperatures of the loggers positioned in the other locations are always smaller than the logger 3. Loggers 5, 6 and 7 present the lowest recorded temperatures overall in the cluster. Loggers 5 and 7 are located between the cluster, the parking areas, and a green space. The parking area provides free space on the south west side of the cluster, thus providing a clearer ventilation path. Logger 6 is placed in an open square formed by the cluster buildings and in a position where the surrounding buildings are in a greater distance than loggers 1, 2, 3, 4 and 8. The thermal imaging throughout the cluster, further confirms that logger 3 position is the hottest in the cluster. An example of a thermal image is shown in Figure 6.

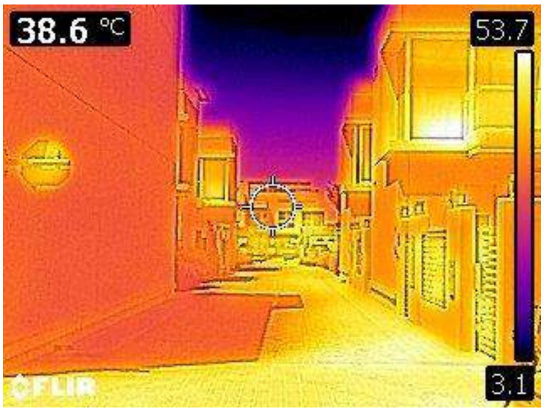
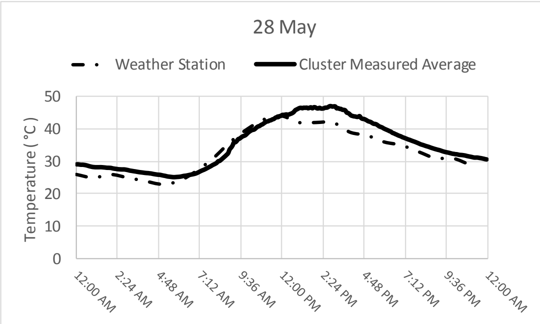
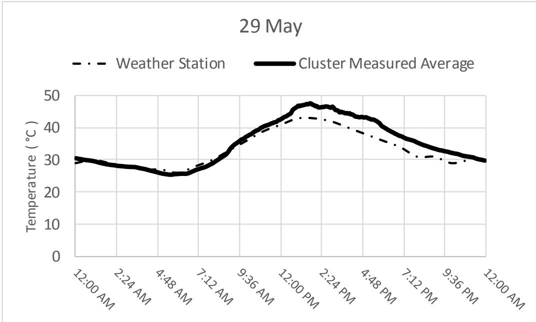


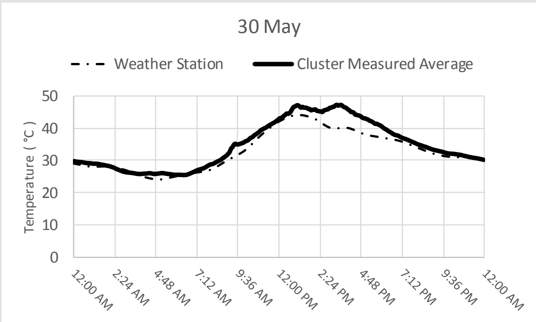
Figure 6. thermal imaging of the logger 3 location

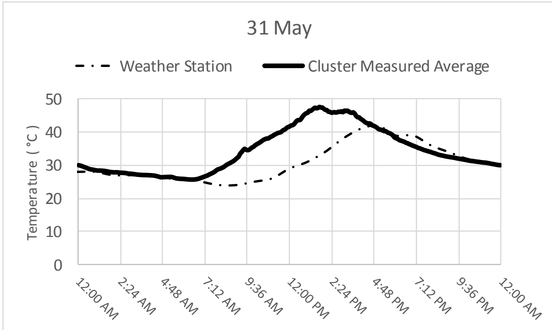
Figure 7, presents the daily temperature difference between the measured temperatures as an average at the cluster and the temperatures recorded at Al Maktum weather station. It is observed that the temperatures measured at the cluster are constantly higher than the ones recorded at the weather station. On an average, the mean temperature difference throughout the cluster for the experimental period ranges between a minimum of 0.02 °C on June the 10^{th} at 2am, and a maximum of 8.53°C on June the 5^{th} at 2pm. The mean UHI intensity is calculated to be 2.44 °C. During night hours, between 9pm to 6am, the mean UHI intensity varies between 1.19 °C to 1.88 °C and between 6am to 9pm it varies between 1.33 °C to 5.39 °C. The extremely high temperatures and solar radiation during the day, could be the reason that the UHI intensity peaks during day hours. The relative humidity in the cluster is generally slightly lower than the relative humidity at the airport weather station. Overall, the relative humidity during the hours 9am to 9pm varies approximately between 10-60% and peaks during night hours.

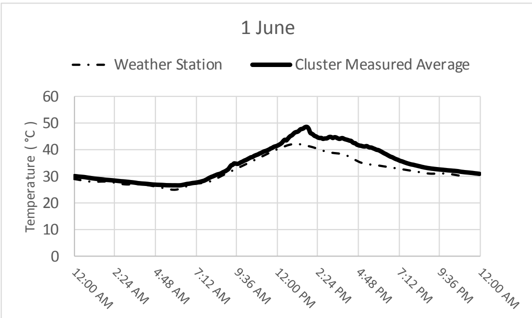
Regarding the spatial temperature distribution in the cluster the hottest spot is identified in the area of logger 3 with 12% higher temperatures than the other loggers, followed by logger 1. Therefore, these are the parts of the cluster that greatest outdoor discomfort is expected for the occupants. The impact of relative humidity in combination with the high temperatures is further explored in the thermal discomfort evaluation, and presented in section 5. Furthermore, the reason of the creation of these hot spots of thermal discomfort is evaluated in section 6 with the use of CFD analysis.

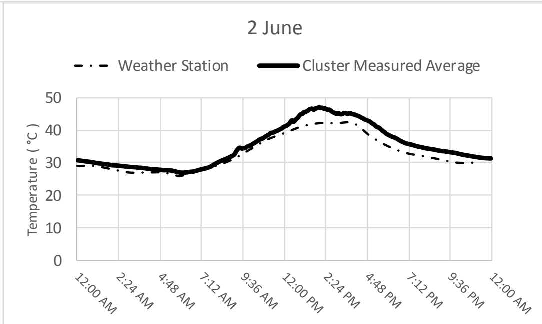

28 May
Weather Station
Cluster Measured Average
Temperature (°C)
0
10
20
30
40
50
12:00 AM
2:24 AM
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
9:36 PM
12:00 AM

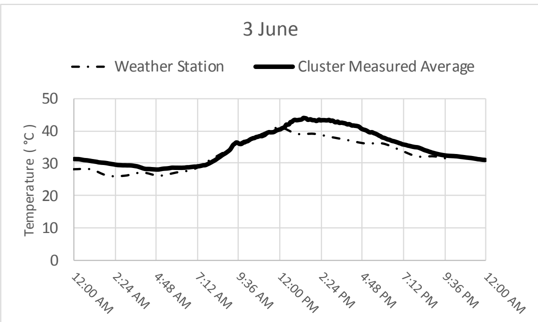

29 May
Weather Station
Cluster Measured Average
Temperature (°C)
0
10
20
30
40
50
12:00 AM
2:24 AM
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
9:36 PM
12:00 AM

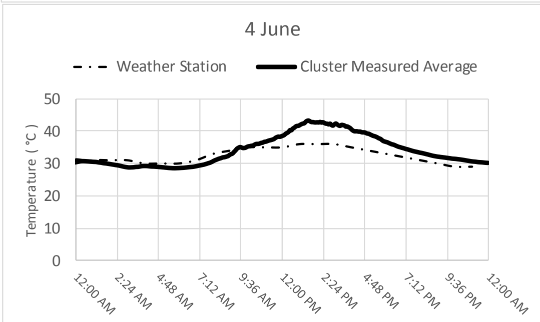

30 May
Weather Station
Cluster Measured Average
Temperature (°C)
0
10
20
30
40
50
12:00 AM
2:24 AM
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
9:36 PM
12:00 AM

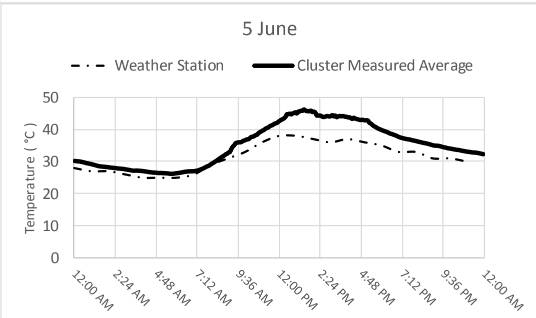

31 May
Weather Station
Cluster Measured Average
Temperature (°C)
0
10
20
30
40
50
12:00 AM
2:24 AM
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
9:36 PM
12:00 AM

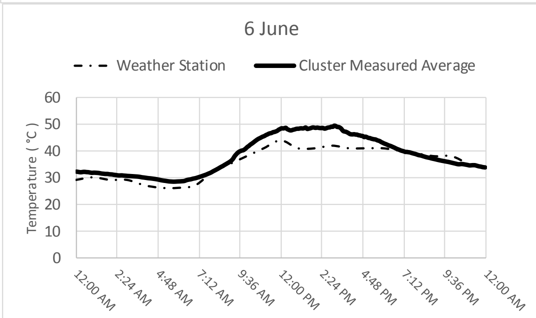

1 June
Weather Station
Cluster Measured Average
Temperature (°C)
0
10
20
30
40
50
60
12:00 AM
2:24 AM
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
9:36 PM
12:00 AM


2 June
Weather Station
Cluster Measured Average
Temperature (°C)
0
10
20
30
40
50
12:00 AM
2:24 AM
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
9:36 PM
12:00 AM


3 June
Weather Station
Cluster Measured Average
Temperature (°C)
0
10
20
30
40
50
12:00 AM
2:24 AM
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
9:36 PM
12:00 AM


4 June
Weather Station
Cluster Measured Average
Temperature (°C)
0
10
20
30
40
50
12:00 AM
2:24 AM
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
9:36 PM
12:00 AM


5 June
Weather Station
Cluster Measured Average
Temperature (°C)
0
10
20
30
40
50
12:00 AM
2:24 AM
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
9:36 PM
12:00 AM


6 June
Weather Station
Cluster Measured Average
Temperature (°C)
0
10
20
30
40
50
60
12:00 AM
2:24 AM
4:48 AM
7:12 AM
9:36 AM
12:00 PM
2:24 PM
4:48 PM
7:12 PM
9:36 PM
12:00 AM

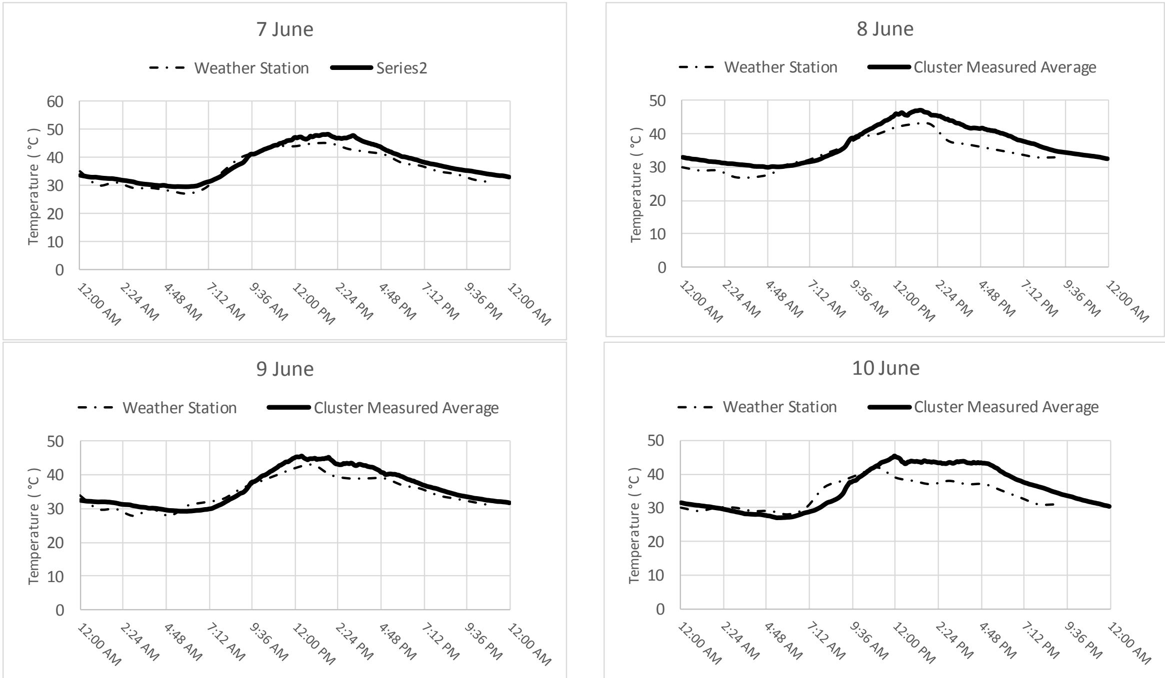


Figure 7. Comparison between the measured temperatures at the cluster and the temperatures recorded at Al Maktum weather station

5. Outdoor Comfort Conditions

As a further indication of the outdoor comfort, the temperature humidity index (THI) is calculated for the experimental period as an average for the cluster. The formula that is used is given in Equation (1):

$$THI = T - 0.55*(1 - RH)*(T - 58) \quad (1)$$

Where T is the air temperature measured in the shade in Celsius and converted in Fahrenheit, and RH is the relative humidity. If the THI is 70 or below, most inactive people are comfortable. If THI = 75, about half are uncomfortable, if THI = 79, nearly everyone is sweating and uncomfortable. In the case that THI is above 80 then extreme discomfort is present and if the THI values are as high as 90, then health and safety is of concern (Schlatter, 1987).

Figure 8 presents the THI in comparison to the temperatures and relative humidity measured in the cluster. As can be seen, the THI is always higher than 70 and in most cases even higher than 75. Considering the limit of 80 which is an indication of extreme discomfort as a benchmark, it is observed that it occurs for temperatures between 30 °C to 50 °C and a wide range of relative humidity values between 12.6% to about 90%. This situation is observed for about 80% of the time of the experimental period, and 100% of the day times. As a result, overall in the cluster, high discomfort is expected during the experimental period. This is not surprising as in the United Arab Emirates the summers are harsh and humid with very high temperatures.

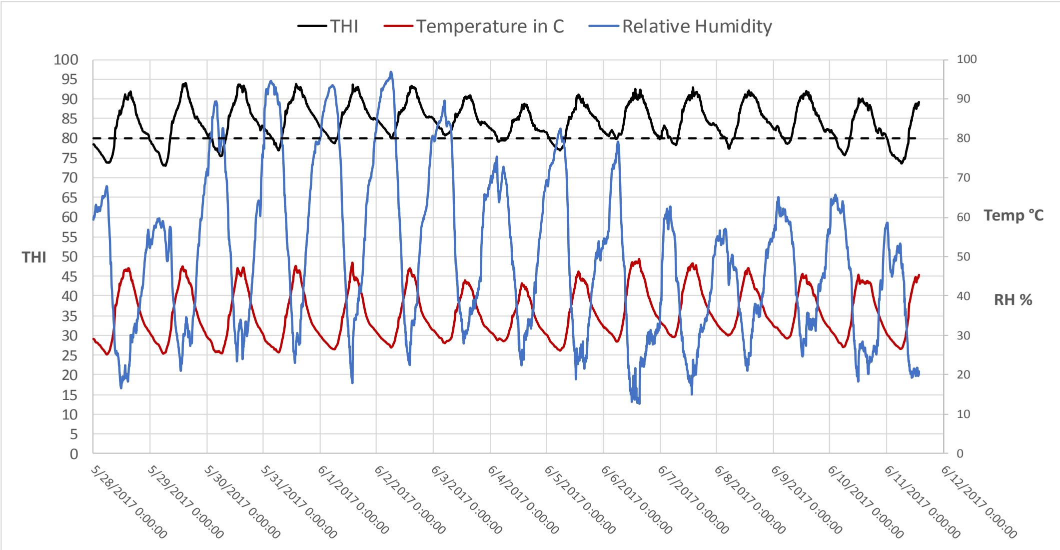


Figure 8. THI in relation to temperature and relative humidity

Further analysis for the data logging positions, indicates that the discomfort is greater in the positions where the measured temperatures are higher. As shown in Figures 9, 10 and 11 the location of logger 3 which has been identified as the hottest in the cluster, presents also the highest potential of discomfort, with an average THI of 84.46 for the whole experimental period. The location of logger 1, which is the second hottest and most humid in the cluster, presents the second highest discomfort, with an average of 84.43 for the experimental period.

In further agreement to the temperature distribution analysis, the position of logger 6 is found to be the one with the least discomfort conditions present, and an average THI of 83.22 for the experimental period.

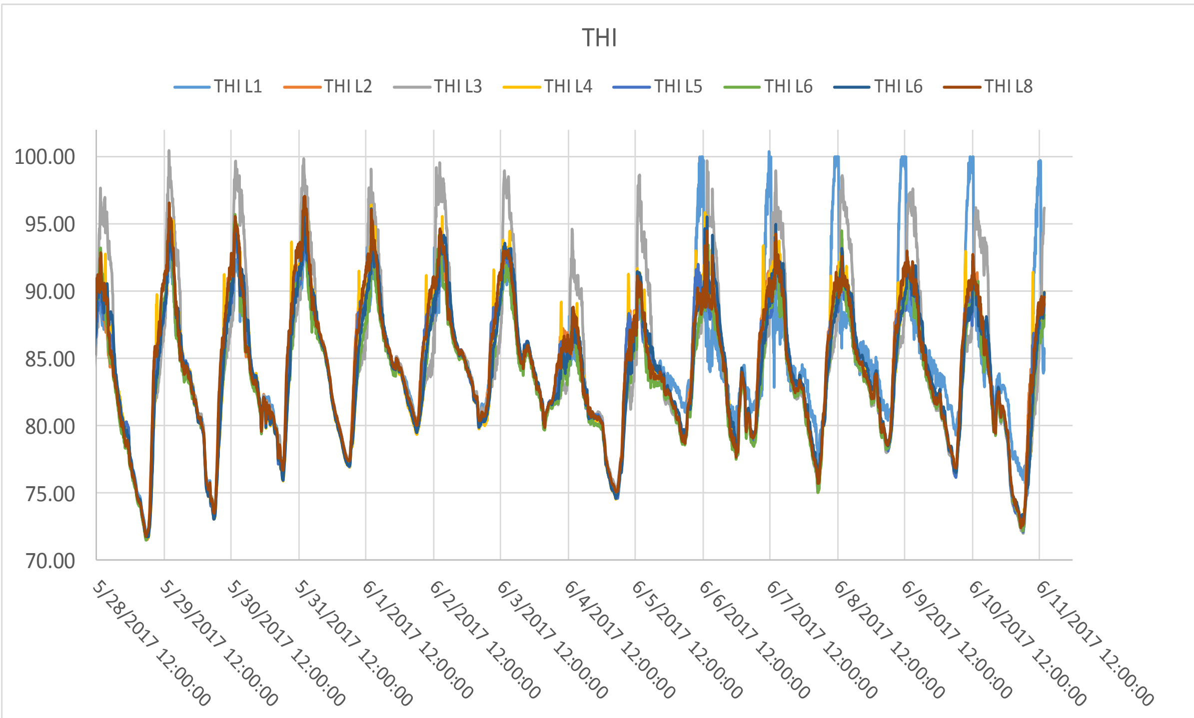


Figure 9. THI for each measurement position during the experimental period

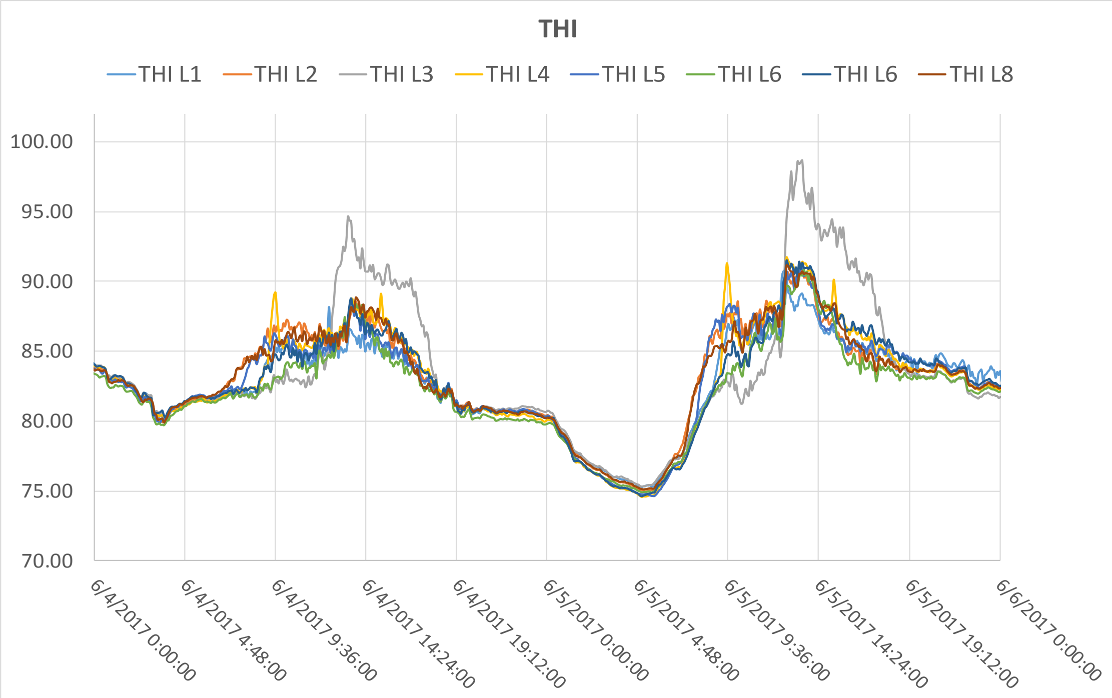


Figure 10. THI for each measurement position for the 4th and 5th of June

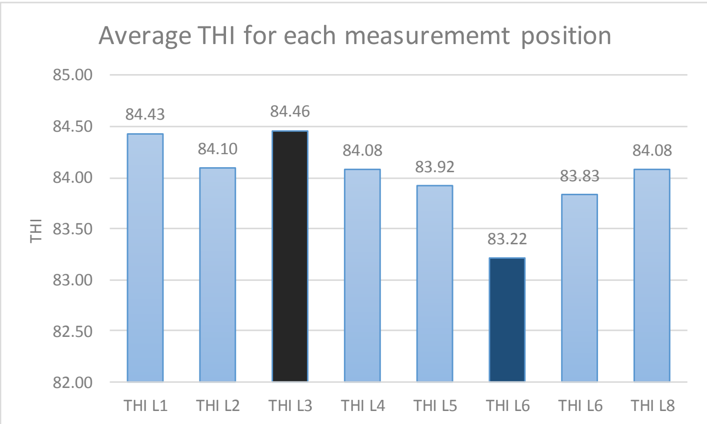


Figure 11. Average THI for each measurement position CFD Results

6. CFD Results

The CFD simulation of the microclimate is conducted for the selected building cluster. Air stagnation, as shown in Figure 12a, was observed at the backward of the building cluster where the temperature is much higher than other areas away from the building. The inlet speed applied to the model was 3.71m/s as per the weather data. Due to the high airflow in the central cluster region, the heat intensity was the lowest at those areas for all models. It was noted that local hot spots are strongly dependent on the geometries of the building cluster and construction materials.

Due to the atmospheric boundary layer around the cluster, the local air velocity at the building height was lower than the inlet boundary condition. Wind direction and speeds will have a significant impact on the hot spots as well. Figure 12b indicates the contour levels of static pressure around the cluster. As expected, higher air pressures are obtained at the windward locations of all the clusters local to the flow inlet, with the maximum pressure value of 3.8Pa. Negative pressure was obtained at the back of the clusters (leeward to the flow inlet) at approximately 2.5Pa.

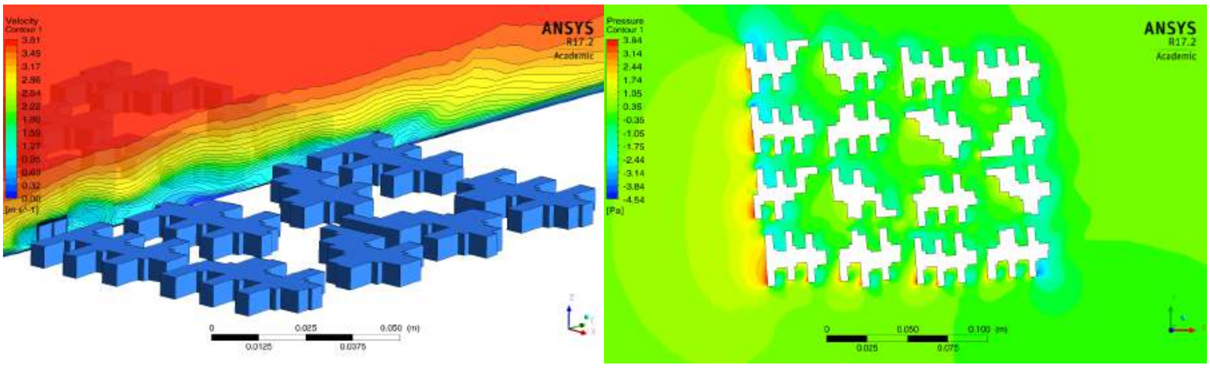
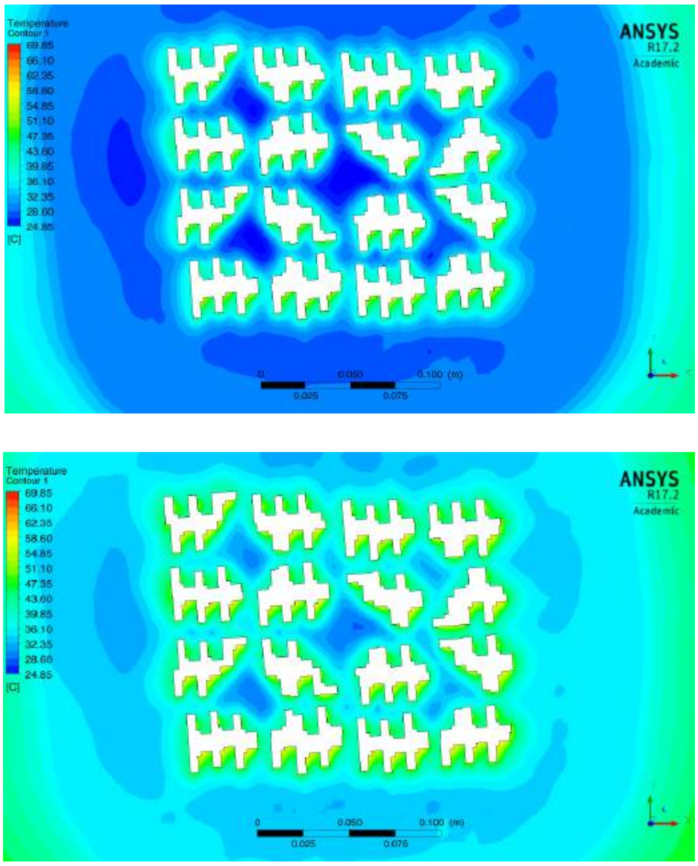


Figure 12. (a) Velocity and (b) static pressure contour levels across the cluster

The CFD results are based on ambient air temperatures of 30 °C, 35 °C and 40 °C to understand the temperature patterns around the cluster, and in accordance to the air temperature ranges of the experimental period. Figure 13 indicates a summary of the temperature findings. As can be observed, the heat intensity was found to be inversely proportional to the air movement through the cluster and the regions of hot spots were localised closer to the boundary walls.



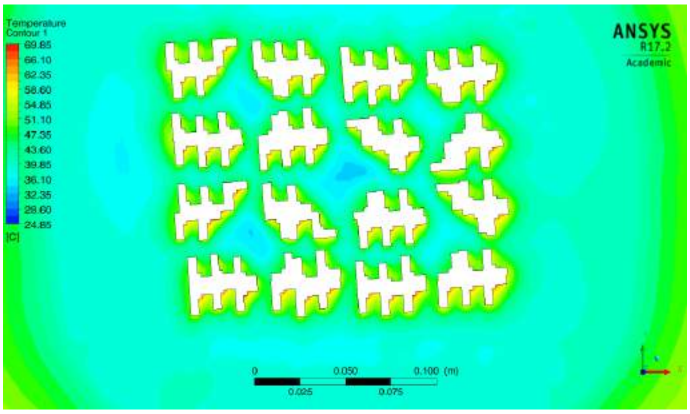


Figure 13. Plan view of the temperature contour levels

Figure 14 displays a quantified temperature profile along the axial direction of the cluster for ambient temperatures ranging between 30 °C and 40 °C. As displayed, the region of high and low heat intensities is consistent through the cluster and is independent of the ambient temperature. The least heat intensity is experienced by the central regions within the cluster (data logging point 6) due to accelerated air movement. However, the amplitude of heat intensity increases with increasing ambient temperature. A maximum temperature increase of 26% was noted when the ambient temperature was 30 °C. This was increased to 40% when the ambient temperature was 40 °C, thereby indicating that urban heat islands augment in magnitude with increasing ambient temperatures. This is a suggestion that under these climatic conditions of extremely high temperatures, the natural ventilation paths would need to be further assisted by other techniques in order to enhance outdoor comfort.

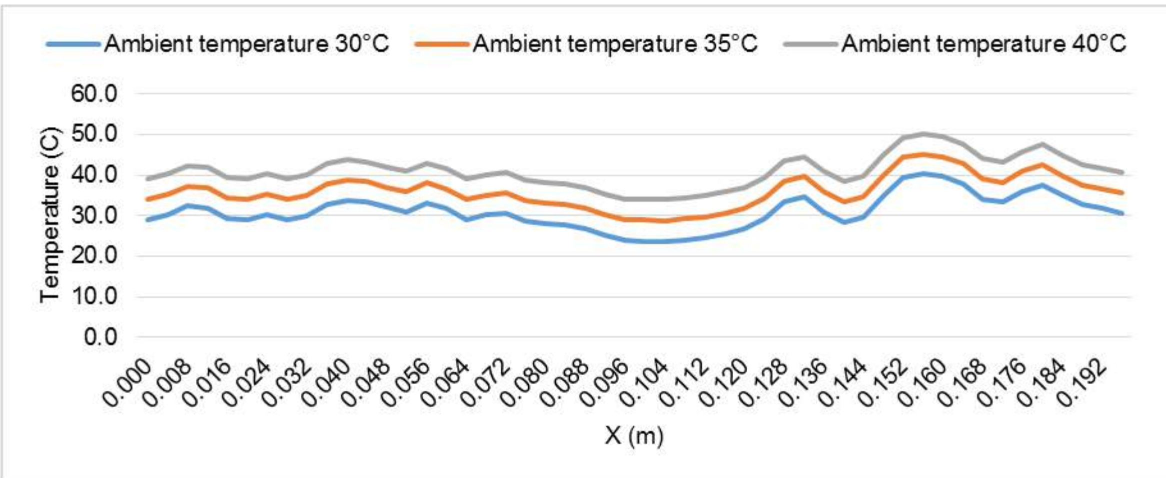


Figure 14. Temperature profiles along the axial direction of the cluster

7. Conclusions and Future Recommendations

This paper presents an analysis of the temperature distribution and its effect on outdoor thermal comfort in Dubai, United Arab Emirates. As Dubai is experiencing rapid urban development and population increase, it is important to evaluate how the residential buildings affect the ambient conditions and consequently the outdoor thermal comfort, particularly for the hot summer period.

A cluster in The Sustainable City residential compound was used as a case study, and air temperature and relative humidity data were measured during peak summer and indicate that 75% of the time temperatures are higher than 30 °C, with peaks of 55 °C. The minimum recorded temperature on average for the whole cluster was 25.13 °C. This extreme temperature range, in combination with the high relative humidity has an effect on outdoor thermal comfort. The temperature humidity index (THI) was calculated, and it was proved that for 100% of the day time and 80% of the overall experimental period, extreme discomfort is present. Furthermore, the hottest locations of the cluster, were also identified as the ones where the highest discomfort is experienced.

The outdoor comfort was further evaluated with a CFD model developed in ANSYS software. The model further indicated that the least heat intensity is experienced by the central regions within the cluster (data logging point 6) due to accelerated air movement as a result of the cluster spatial design and the broader space between buildings. Furthermore, the amplitude of heat intensity increases with increasing ambient temperature, thus eliminating the cooling effect of the ventilation paths within the cluster.

As a conclusion, mitigation strategies are necessary in order to improve this condition and result in lower air temperatures within the cluster. At the current state, The Sustainable City follows the local vernacular of the United Arab Emirates, with sand colored buildings, built at a close distance with limited vegetation present. Further work of the authors, will focus on evaluating the effect of increased green spaces around the cluster, external shading and different building coatings. Furthermore, the effect on a building cooling demand level will be evaluated with the use of IESVE software.

8. Acknowledgments

This project is partly funded by the Global Challenges Research Workshop Call 2016 (RCUK, 1278-R20-B15R12024). Thanks are also due to The Sustainable City facilities management for allowing access for the experimental data measurements

9. References

Indraganti, M., & Boussaa, D. (2017). An adaptive relationship of thermal comfort for the Gulf Cooperation Council (GCC) Countries: The case of offices in QatarMadhavi. *Energy and Builings, 159*, 201-212.

Al-Sallal, K., & Al-Rais, L. (2011). Outdoor airflow analysis and potential for passive cooling in the traditional urban context of Dubai. *Renewable Energy, 36*, 2494e2501.

Brumana, G., Franchini, G., & Perdichizzi, A. (2017). Design and performance prediction of an energy + building in Dubai. *Energy Procedia, 126*, 155-162.

Diamond Developers. (2017). *The Sustainable City*. Retrieved November 2017, from http://www.thesustainablecity.ae/

Dubai World Central (DWC). (2017). *Dubai World Central (DWC).* Retrieved July 2017, from http://www.dubaiairports.ae/corporate/about-us/dwc-dubai-world-central

Flir. (2017). *Introducing FLIR C2*. Retrieved July 2017, from http://www.flir.com/instruments/display/?id=66732

Gemini data loggers. (2017). *Tinytag View 2 TV4500*. Retrieved July 2017, from http://gemini2.assets.d3r.com/pdfs/original/1601-tv-4500.pdf

Hassid, S., Santamouris, M., Papanikolaou, N., Linardi, A., Klitsikas, N., Georgakis, C., & Assimakopoulos, D. N. (1999). The effect of the Athens heat island on air conditioning load. *Energy and Buildings, 32*(2000), 131–141.

Kolokotroni, M., & Giridharan, R. (2008). Urban heat island intensity in London: An investigation of the impact of physical characteristics on changes in outdoor air temperature during summer. *Solar Energy, 82*(2008), 986–998.

Levermore, G., Parkinson, J., Lee, K., Laycock, P., & Lindley, S. (2017). The increasing trend of the urban heat island intensity. *Urban Climate*.

Safa Achour-Younsia, F. K. (2016). Outdoor thermal comfort: Impact of the geometry of an urban street canyon in a Mediterranean subtropical climate – Case study Tunis, Tunisia. *Procedia - Social and Behavioral Sciences*, 689 - 700.

Schlatter, T. W. (1987). Temperature-humidity index . In V. N. Reinhold (Ed.), *Climatology* (pp. 837-838). Spriger.

Taleb, D., & Abu-Hijleh, B. (2013). Urban heat islands: Potential effect of organic and structured urban configurations. *Renewable Energy, 50*(2013), 747 - 762.
The World Bank. (2014). *Energy use (kg of oil equivalent per capita)*. Retrieved November 2017, from https://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE?locations=AE
The World Bank. (2017). *Climate Change Knowledge Portal*. Retrieved November 2017, from http://sdwebx.worldbank.org/climateportal/index.cfm?page=downscaled_data_download&menu=historical
Weather Underground. (2017). *Al Maktoum International, AE*. Retrieved July 2017, from https://www.wunderground.com/weather/ae/al-maktoum-international/OMDW

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Development of a Mexican Standard of Thermal Comfort for Naturally Ventilated Buildings

N. Morgan[1] and G. Gomez-Azpeitia[2]

[1] Faculty of Architecture and Design, University of Colima, Km. 9 - Carr. Colima-Coquimatlán, 28400, Coquimatlán, Colima, México. nmorgan@ucol.mx;
[2] Faculty of Electronic Instrumentation and Atmospheric Sciences, Universidad Veracruzana, Universitario Gonzalo Aguirre Beltrán, Zona Universitaria, 91090 Xalapa de Enríquez, Veracruz, México. ggomez@ucol.mx.

Abstract: This paper presents results of the first stage of the project Development of a Mexican Standard of Thermal Comfort for Naturally Ventilated Buildings (MSTC-NVB). The project is based on the adaptive thermal comfort approach. The aim of such standard is to determine internal thermal conditions appropriate to climates of Mexico as well as their inhabitants´ lifestyles. Thus, this standard could serve as a useful tool supporting buildings' design in order to decrease their need of air conditioning; which increases day by day as a consequence of global warming. In the last ten years, a large number of thermal comfort field studies have been conducted in different climate regions of Mexico (temperate and hot zones, both dry and humid); from these a database consisting of 8,018 surveys was created, comprising 38 field studies conducted, in accordance with ISO 10551, ASHRAE 55 and ISO 7726, at different times in 13 different cities. Raw data was analyzed, standardized, debugged and integrated. For the meta-analysis the neutral temperatures were estimated by the Griffiths method, whose regression coefficient was determined from the quotient of the standard deviation (SD) of the votes of thermal sensation and the standard deviation of the registered internal temperatures.

Keywords: Thermal comfort, adaptive approach, thermal sensation, neutral temperature.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC, 2014) in its most recent report has indicated that in 2010 buildings accounted for 32% of the total global final energy use (IEA, 2013), more than half the total consumption in buildings is due to heating or cooling the space. This amount can increase due to population growth and people's lifestyles. Mexico (member of the OCDE (Organization for Economic Co-operation and Development)) is expected to have an increase in population by 2030, as well as 50% increase of total energy consumption attributed to industrial activity and acquisition of household devices, such as air conditioning equipment (OECD/IEA, 2015), that is already been used by the population according to their economic possibilities as a strategy to promote a more comfortable internal environment. This trend is of serious concern.

Considering that "Both the comfort of the occupants of a building and the energy the building consumes are closely linked to indoor temperature" (Nicol, 1993), and that the lifespan of buildings is 30 (nonresidential buildings) or 50 (housing) years (DOF, 2012), this indicates that the way buildings are currently built will have an effect on the way users consume energy in said buildings for the next 30 to 50 years.

Prior to 1970, studies regarding thermal comfort had already been carried out in order to establish parameters for the appropriate thermal environmental conditions; two of the main approaches being developed were: the *predictive approach* which analyzes the thermal sensation of people inside controlled climatic chambers, and the *adaptive approach* where people perform their usual activities in their natural environment. Derived from these studies, thermal comfort standards were established, with the application of mathematical models to determine the environmental conditions that would allow the majority of users to experience a thermal comfort sensation.

The first international standard *ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy* was published in 1966, based on the predictive approach (Brager & de Dear, 2000); in 2004 the ASHRAE RP-884 project results were integrated, based on the adaptive approach. Later the *ISO Standard 7730: Analytical determination and interpretation of thermal comfort, using calculation of the PMV and PPD indices and local thermal comfort* was published in 1984, based on the predictive approach with equations proposed by Fanger for the calculation of air conditioning for closed spaces. Regional standards have also been published, for instance the *EN 15251: Indoor Environmental Parameters for Design and Assessment of Energy Performance of Buildings*, which was the first standard based on the adaptive approach (by 2002 the SCAT's project results (Nicol & McCartney, 2001) were included); or the *Standard of Thermal Comfort for Warm-Humid Tropics* and more recently the Indian Model For Adaptive Comfort (IMAC) (Sanyogita, et al, 2016).

Regarding Mexico, in the last decade, field studies on thermal comfort have been carried out under the adaptive approach in different regions of Mexico. The amount of data obtained is sufficient for the formulation of a Mexican thermal comfort standard for naturally ventilated buildings. This standard will allow us to determine a more suitable indoor environmental set of conditions for living spaces, according to the climate as well as the customs and lifestyles of its inhabitants who are not familiar with the use of artificial air conditioning equipment.

To obtain the mathematical model for the Mexican standard, we have taken the raw data of 8,018 surveys from 38 field studies conducted in 13 different cities of Mexico, which have been standardized, debugged and integrated in a general database for our meta-analysis. For the statistical process we have taken the guidelines made by authors who have participated in the obtaining of mathematical models of international standards.

2. Methodology

The adaptive approach has proven to be more suitable for determining environmental conditions in *'free-running'* buildings (Nicol F., 2004). Due to the fact the Mexican population usually lives in naturally ventilated buildings, it was decided to conduct field studies on thermal comfort based in the adaptive approach. Therefore for the development of the Mexican standard, the guidelines made by the developers of previous standards on adaptive thermal comfort such as ASHRAE 55 (de Dear et al, 1997) (de Dear et al, 1998), EN 15251 (Nicol & McCartney, 2001) and IMAC (Sanyogita et al, 2016) were analyzed.

Firstly a general description of the field studies previously conducted in Mexico is presented, thus establishing the data sources that integrated the general database. Secondly the standardization and debugging process of the raw data obtained from the field studies is described prior its integration to the general database. Thirdly statistical procedures were applied to the data aforementioned; so that its meta-analysis could be performed.

2.1. Description of field studies conducted in Mexico

In each study, the researchers conducted an analysis to determine the city, climate, season, and population to be analyzed. The field studies were carried out taking into account the following criteria:

The evaluation of the perception of the indoor environment was by means of surveys according to the indications of the standards ISO 10551 and ASHRAE 55, a thermal sensation scale was used (ASHRAE 55 or Bedford (1936)).

The measurement of indoor environmental variables was recorded simultaneously during the surveys. The equipment and instruments used met the requirements indicated in the normative, as well as the calibration, operation and location with respect to the persons surveyed. Due to the capacity of acquisition and disposition of equipment, the measurements of the variables were taken at a height (waist level). The equipment and measuring instruments used were: QUES Temp 36 and 32 with omnidirectional anemometer (WBT,DBT with a range of 0 – 100 °C and a ± 0.5 °C accuracy; RH with a range of 0 – 100 % and a ±5.0 % accuracy), Air Probe Accessory (*v* with a range of 0 – 20 m/s with a ± 0.50 m/s + 4% accuracy), HOBO U23-001 Pro v (WBT out with a range of 0 – 70 °C and a ±0.2 °C accuracy, RH out with a range of 0 - 100 % RH and a ±0.25 % accuracy), Kestrel mod. 4 (RH with a range of 5 – 95 % and a ±3.0 % accuracy, with an accuracy of *v* ± 0.1 m/s to ±0.01 m/s) and Anemometer Delta (*v* with a range of 0 – 40m/s and a ± 0.05 m/s accuracy). A list of articles including thorough descriptions and specifications is included in Appendix A.

2.2. Processing of data

Through letters, researchers were invited to collaborate in this project, to share the databases of their studies; 18 researchers have contributed by providing their databases. The total sample of the database consists of 8,018 surveys, from 13 different cities with diverse climates in Mexico (warm sub-humid, warm humid, dry semi-cold, warm dry and temperate sub-humid) (see Table 1). Figure 1 shows the geographical origin of the studies carried out in Mexico.

Figure 1. Geographical origins of the field studies for MSTC-NVB database.

Table 1. Field studies included in MSTC-NVB database

Type of climate	City	Sample (n)
Warm sub-humid	Colima, Colima.	608
	Culiacán, Sinaloa.	151
	Tuxtla Gutiérrez, Chiapas.	312
Warm humid	Manzanillo, Colima.	502
	Culiacán, Sinaloa.	942
	Veracruz, Veracruz.	152
	Mérida, Yucatán.	2027
Dry semi-cold	Pachuca, Hidalgo.	1556
Warm dry	Hermosillo, Sonora.	295
	Mexicali, Baja California.	235
	La Paz, Baja California Sur	316
	Chihuahua, Chihuahua.	269
	Cd. Juárez, Chihuahua.	262
Temperate sub-humid	Zona metropolitana del Valle de México.	391
	Total:	8018

Indices calculation within the data base: from the registered values of the climatic variables, indices required for the process of statistical analysis were calculated. For indoors the indices considered were: t_{mr} (mean radiant temperature), t_o (operative temperature) and CET (corrected effective temperature) which were calculated from the known data: DBT (dry bulb temperature), BGT (black globe temperature) and RH (relative humidity); for the outdoor WBT (wet bulb temperature), the calculations were made from the known data DBT and RH. In Mexico there is a climatic diversity due to the presence of humidity, hence it was considered necessary to include the calculation of the CET. These indices were calculated per each survey that integrated every single one of the 38 studies.

From the integrated database, 23.30 % of the surveys recorded the outdoors' meteorological variables as well as the indoors'; for the rest of the studies, the outdoors' meteorological variables were obtained from the meteorological program *METEONORM*.

Standardization of data for the new database (meta-file): the databases of the field studies were carried out according to the criteria of each researcher, so it was necessary to standardize criteria and values when incorporating them into the meta-file format for a better management of the data during the analysis process.

Table 2. Clo values for MSTC-NVB

Type	Description of ensemble	Man	Woman
1	Light: t-shirt, walking shorts, shoes /sandals.	0.22	0.22
2	Normal: short-sleeve knit, straight trousers, socks, shoes.	0.40	0.35
3	Formal: short-sleeve knit, jacket, straight trousers, socks, shoes.	0.82	0.71
4	Winter: long underwear top, sweater long-sleeve, jacket, straight trousers, socks, boots.	1.33	1.33
5	Artic: long underwear top, sweater long-sleeve (thick), jacket (thick), straight trousers (thick), socks (thick), boots.	1.48	1.48

Source: own elaboration with information from ASHRAE 55-2013

The criteria taken into account for the standardization of the data were these: environment control devices, time inside the room (less than 15 minutes / more than 15 minutes.); sex; type of clothing (see Table 2); thermal acceptance; thermal sensation (7-point scale ASHRAE 55, see Table 3); thermal preference and ventilation preference.

Table 3. Thermal Sensation scale used for MSTC-NVB

Vote TS	Description
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Source: ASHRAE 55-2013

Debugging surveys: it was necessary to analyze the information of the surveys in each study to detect those that could contain inconsistent information that could alter the results. The surveys were refined according to the following exclusion criteria:

- Buildings in which HVAC systems were active.
- Respondents with less than 15 minutes inside the room, when according to ASHRAE, 2013, 15 minutes is the minimum time suggested for an individual to be able to stabilize.
- Respondents who had just finished intense physical activity.
- The BGT (black globe temperature) values were greater than 10 °C with respect to the DBT (dry bulb temperature), this could indicate that at the time of the survey a heat radiating device, such as a stove, fireplace, etc. could be found indoor; which could alter the thermal sensation reported by the person. The ASHRAE-55 considers the differences between air temperatures and mean radiant temperatures below 4 °C. For this research, we take the criterion of excluding those that exceed 2.5 times the value suggested by the norm, that is, 10 K.
- Respondents less than 12 years old.

2.3. Statistic analysis

Only the surveys with consistent data were integrated into the meta-file, to which the statistical processes were applied.

2.3.1. Derivation of sensitivity to interior temperature changes

In order to minimize errors in the statistical analysis due to the wide variation of values during long periods, the method of derivation of the sensitivity to the changes of indoor temperature was used as Humphreys proposed (2013, 2016). Within each study, the included surveys were grouped daily and in each subset the following equations were applied.

For the thermal sensation variation:

$$\Delta vST = vST - vTS\_mean \qquad (1)$$

where:

Δ vST : variation of the votes of thermal sensation (daily).
vTS : vote of thermal sensation recorded in each survey.
vTS_mean : mean vote of thermal sensation calculated from votes recorded during the day in question.

For the operative temperature:

$$\Delta t_o = t_o - t_o\_mean \quad (2)$$

where:

Δt_o : variation of operative temperature (daily).
t_o : operative temperature recorded in each survey.
t_o_mean: mean operative temperature of the day in question.

2.3.2. Determination of the regression coefficient (b)

To obtain a regression coefficient that best fits the line from which the mathematical model was obtained, two types of regression coefficients or gradient were calculated in each study from the set of values of operative and effective temperature, with the following equations (Humphreys et al, 2013):

Mean coefficient:

For t_o: $$b = \sigma TS / \sigma t_o \quad (3)$$

where:

σ TS : standard deviation of the votes of thermal sensation.
σt_o : standard deviation of operative temperature.

Adjusted coefficient:

For t_o: $$b_{adj} = b * (\sigma^2 t_o) / (\sigma^2 t_o - \sigma^2_{err}) \quad (4)$$

where:

b_{adj} : adjusted regression coefficient.
$\sigma^2 t_o$:variance of the operative temperature of the set of daily values.
σ^2_{err} : error variance of the operative temperature from daily values of each study.

Three exercises were carried out to determine the regression coefficient in which the previous equations were applied (mean coefficient and coefficient adjusted): A) analysis study by study, in which the values of the regression coefficient were calculated individually within each study, concentrated and averaged; B) general analysis (all studies), data from 38 studies were integrated within an Excel sheet; to which the daily analysis procedure indicated in the previous section was applied to all data as if it were a single study to calculate the values of the mean gradient and the adjusted gradient; and C) analysis by type of building, the database was divided into two subsets (Humphreys M., 2017), the first subset included studies conducted in school and hospital buildings, in the second subset were included the rest of the studies that were carried out in dwellings.

2.3.3. Calculation of the neutral temperature in each study

For the calculation of the neutral temperature of each study, the value of the regression coefficient (b) was applied in the equation proposed by Griffiths (Griffiths, 1990) with the following equations:

For t_o: $$Tn = t_o\_mean - (TS\_mean / b) \quad (5)$$

where:

Tn : neutral temperature.
t_o_mean : mean operative temperature from the study.
TS_mean: mean thermal sensation from the study.
b : regression coefficient.

2.3.4. Meta-analysis

The set of values for the independent variable X were the average values of the outdoor temperatures of each study, and the set of values of the dependent variable Y were the Tn values of each study. Each one of the values for X and Y were represented in scatter diagrams from which the equation of the line was obtained which is the resulting mathematical model for the MSTC-NVB. This process was applied to operative temperature and corrected effective temperature.

3. Results

In order to establish a Mexican thermal comfort standard for naturally ventilated buildings (MSTC-NVB), data from field studies previously conducted in Mexico were processed and analyzed as described in the previous sections. Out of the total sample consisting of 8,018 surveys, 6,471 surveys (80.71 %) were included to a meta-file after the information was processed and debugged.

3.1. Analysis into proportions

Of the total sample, 39 % of respondents expressed a neutral thermal sensation. The neutrality votes were presented in a temperature range of 12.75 to 41.53 °C (28.78 K), as indicate in the Table 4 and Figure 2.

Table 4. Proportion of thermal sensation votes and indoor temperatures.

Vote TS	Amount of votes	%	Range t_o (°C)	Oscillation
+3	594	9.18	23.35 - 44.66	21.31
+2	813	12.56	14.80 - 43.14	28.34
+1	1337	20.66	15.95 - 44.69	28.74
0	2525	39.02	12.75 - 41.53	28.78
-1	916	14.16	12.75 - 45.17	32.42
-2	238	3.68	9.29 - 32.52	23.23
-3	48	0.74	12.30 - 33.19	20.89

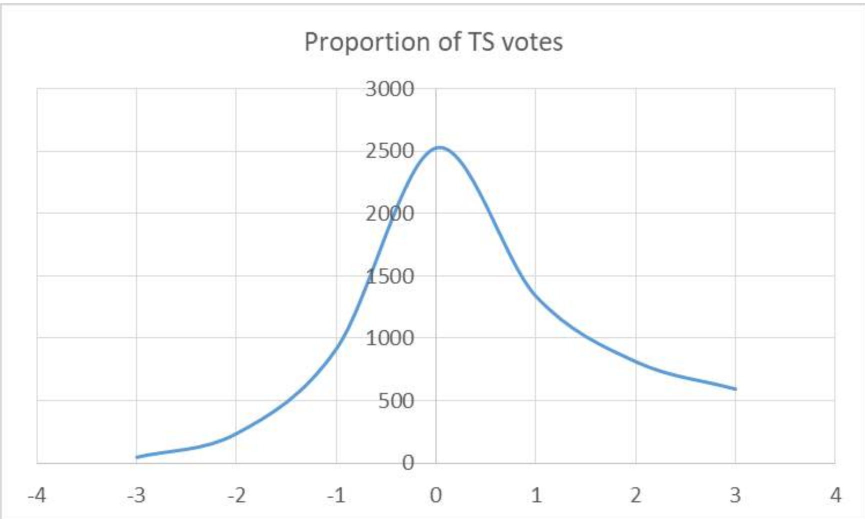


Figure 2. Proportion of thermal sensation vote

As shown in Figures 3 and 4 there was a strong correlation between the preferred interior temperatures and the votes of thermal sensation (r= .89 for t_o and r= .86 for CET); also between indoor temperature and outdoor temperature (r= .86 for t_o and r= .81 for CET); this indicates a strong dependence of the preferred neutral temperature related to outdoor temperature. The coefficient of determination r^2 = .74 (t_o) indicates that the 74 % of the neutral temperature could be attributed to the outdoor temperature.

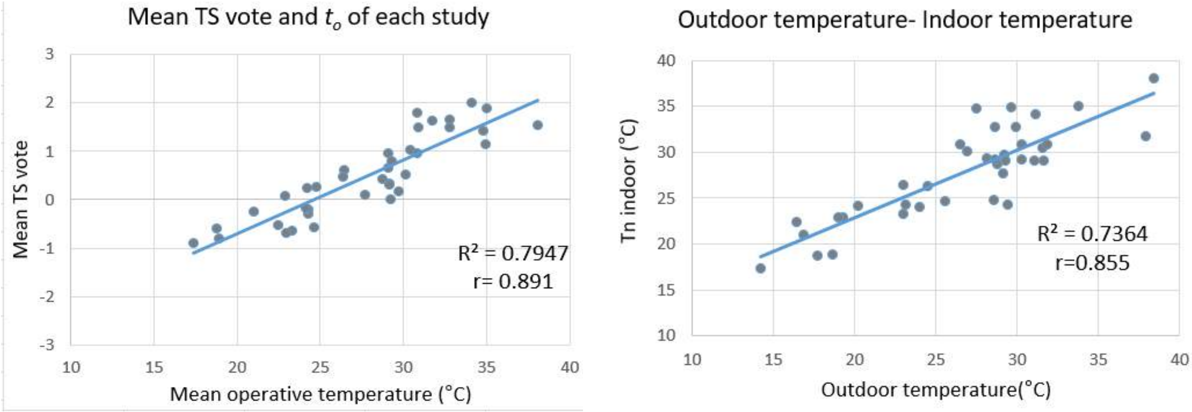


Figure 2. TS vote regarding t_o; and relationship between t_o and outdoor temperature

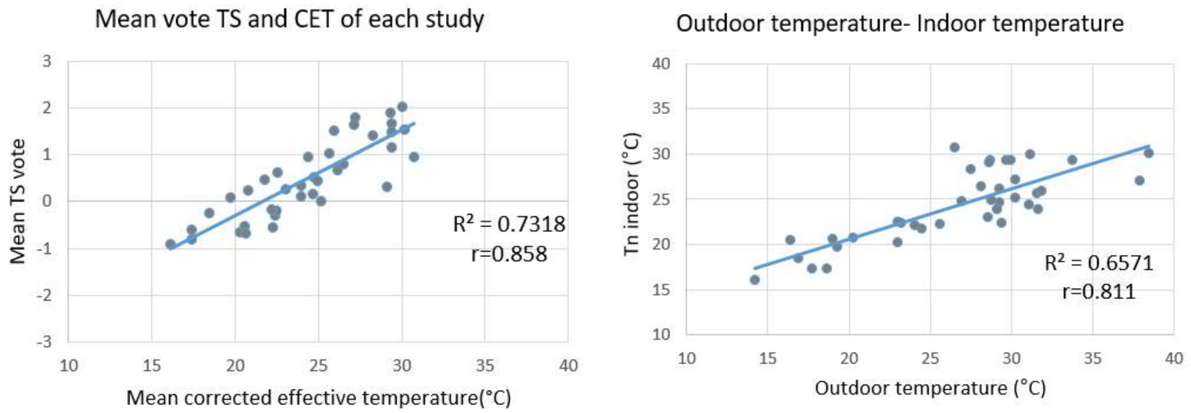


Figure 3. TS vote regarding to CET; and CET regarding to outdoor temperature

3.2. Regression coefficient:

The different values for the regression coefficient were concentrated as shown on Table 5 and compared with those used in the previous standards (see Table 6). After analyzing the values obtained, it was decided to use the mean coefficient with a value of 0.50 for $\boldsymbol{t_o}$ (rounding off 0.463) and 0.70 for CET (rounding off 0.710).

Table 5. Values of regression coefficients

	Mean gradient		Adjusted gradient	
	t_o	CET	t_o	CET
Study by study	0.463	0.710	0.117	0.191
General (all studies together)	0.250	0.262	0.156	0.061
Schools and Hospitals	0.563	0.686	0.101	0.119
Dwellings	0.432	0.717	0.122	0.213
Gradient to apply	0.50	0.70		

Table 6. Regression coefficients in previous standards

Standard	Mean gradient	Adjusted gradient
ASHRAE 55	0.270	0.432
SCAT's	0.361	0.458
IMAC (India)	0.130	0.160

Source: Humphreys, 2013 and Sanyogita et al, 2016

Finally, the meta-analysis process generated the scatter diagrams from which the mathematical model was obtained for the Mexican standard, presenting the following results:

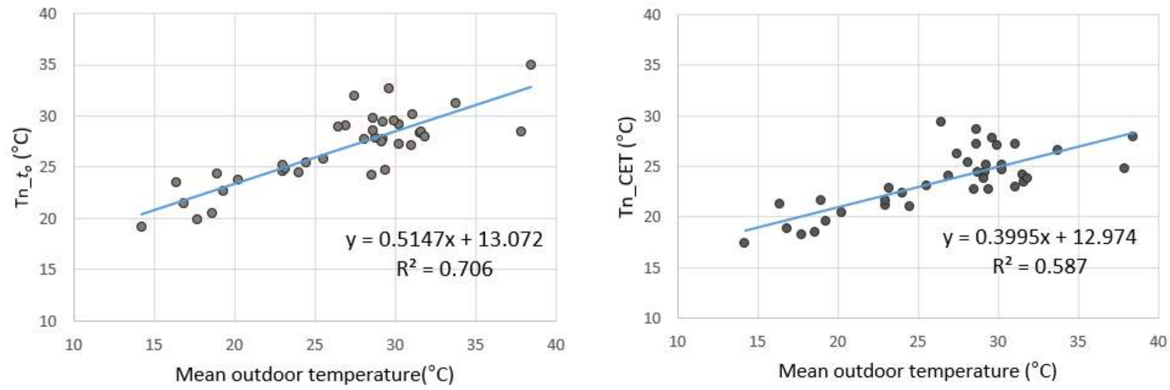


Figure 5. MSTC-NVB model for t_o and CET.

For t_o (operative temperature):

Tn = 0.51 Outdoor temp. + 13.07 **r=.84** **r^2=.71**

For CET (corrected effective temperature):

Tn = 0.39 Outdoor temp. + 12.97 **r=.77** **r^2=.59**

Other findings:

- The mean regression coefficients 0.50 for operative temperature and 0.70 for CET were more suitable for the present research (study by study analysis).

- High correlation values (r = 0.86 for t_o and r = 0.81 for CET) were obtained between neutral temperature and outdoor temperature.

- The average neutral temperature of the entire database was + 0.50 (between neutral and slightly warm), with temperatures ranging from 12.75 to 41.53 °C (28.78 K) for operative temperature.

Table 7. Summary of results and findings

	Top		CET	
Mathematical model	Tn = 13.07 + 0.51 Outdoor temp		Tn = 12.97 + 0.36 Outdoor temp.	
Correlation	r=.84	r^2=.71	r=.77	r^2=.59
Regression coefficient	0.50		0.70	
Tn mean	+0.50		+0.50	
Temperature range	28.78 K		22.83 K	
Correlation Tn/Out.	0.86		0.81	

4. Comparison with international models

For the comparison process, the mathematical models presented by the international standards ASHRAE 55, EN 15251 and the Mexican standard, were applied for the calculation of the neutral temperatures (t_o) in the studies that integrated the database of this research and presented in scatter diagrams. In both scatter diagrams it is observed that the inclination of the line is more pronounced for the Mexican standard, because the regression coefficient obtained for this standard was higher than those used in international standards.

This indicates that this mathematical model allows for a more precise prediction of the neutral temperature preferred by Mexican users, than what recommended by international standards (see Figure 6).

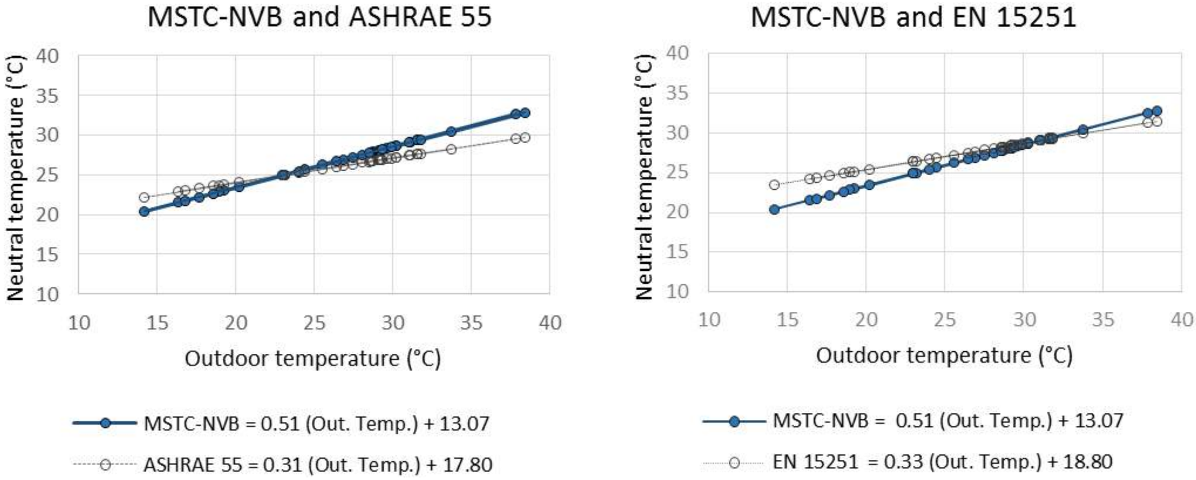


Figure 6. Scatter diagrams for comparison of the Mexican standard with international standards.

5. Discussion and conclusions

Through this research, the mathematical model for the MSTC-NVB was obtained (based on a meta-analysis of data from previously conducted field studies carried out in 13 cities from different climatic regions of Mexico) in order to provide a more suitable standard to the climatic conditions as well as the culture and lifestyles of its inhabitants who mostly live in naturally ventilated buildings.

Therefore, it was expected that the Mexican standard would differ from international standards, and that the predicted neutral temperature values would be warmer (around + 4.0 °C than the international ones). As a result of an exercise to compare the results obtained from the mathematical model MSTC-NVB vs ASHRAE 55 and EN 15251, differences of + 0.73 and -2.07 °C were obtained respectively (with more noticeable changes in extreme dry warm climates with little more than + 3 °C with respect to ASHRAE 55), so it is determined that the mathematical model for Mexican standard does differ with respect to international standards but the value of + 4.0 °C was overestimated.

The mean coefficient of the study by study analysis was more appropriate because this database is mainly integrated of studies conducted in dwellings in which the indoor temperature range is usually wider and users have more opportunities of adaptation than those in office buildings. Obtaining a specific regression coefficient for this standard allows for the calculation of more suited neutral temperatures to the climate and lifestyle of Mexican users.

The coefficient of determination r^2=.74 for t_o between neutral temperature and outdoor temperature obtained was very similar to r=0.76 as reported in the Humphreys's analyses (2013). This could be due to the fact that this study included only naturally ventilated buildings in which people are more influenced by the outdoor temperature, in addition to their habits or lifestyle.

We also found a greater amplitude of neutral temperatures: 28.78 K (12.75 to 41.53 °C) compared to 16 K (13 to 33 °C) presented in the findings by Humphreys(1975, 2016); this indicates that people, particularly from extreme hot climates, felt comfortable at temperatures above 40 °C.

Additionally, we consider that the use of the CET for obtaining neutral temperature is more appropriate because Mexico has a climatic variety influenced by the effects of humidity and wind speeds.

The finding of this mathematical model presents a useful tool to both building designers and builders, for it allows them to weigh the environmental conditions inherent to Mexico affecting the final user's thermal sensation; the former in order for them to determine better design strategies. Advocating for the implementation of passive strategies to achieve and preserve comfort temperatures, and if the use of mechanical conditioning is necessary, this can be activated in a moderate way which contributes to the reduction of electrical energy consumption and consequently to the mitigation of greenhouse gas emissions and therefore to global warming and current climate change.

Acknowledgments

The authors would like to express our thanks to institutions such as CONACyT (Consejo Nacional para la Ciencia y la Tecnología) [National Council for Science and Technology] and CONAVI (Comisión Nacional de Fomento a la Vivieda) [National Commission for House Fostering] for financing this project, as well as the field studies previously conducted from which our database was drawn. We also appreciate the contribution of the following researchers for making available their raw database which were later integrated in the MSTC-NVB database:

Adalberto Tejeda Martínez, *Guillermo García Grijalva* y *Ramos Herrera Zavaleta,* Universidad Veracruzana [Veracruz University]; *Irene Marincic Lovriha y José Manuel Ochoa de la Torre*, Universidad de Sonora [University of Sonora]; *Raúl Pavel Ruíz Torres*, Universidad Autónoma de Chiapas [Autonomous University of Chiapas]; *Ramona Alicia Romero Moreno y Gonzalo Bojórquez Morales*, Universidad Autónoma de Baja California [Autonomous University of Baja California]; *Óscar Reséndiz Pacheco y Elizabeth Chávez Pérez*, Universidad Autónoma de Baja California Sur [Autonomous University of Baja California Sur]; *María Milagrosa Pérez Sánchez y Carmen García Gómez*, Universidad Autónoma de Yucatán [Autonomous University of Yucatán]; *Armida Llamas Estrada*, Universidad Autónoma de Sinaloa [Autonomous University of Sinaloa]; *Luis Carlos Herrera*, Escuela de Arquitectura y Diseño ISTHMUS Norte [School of Architecture and Design ISTHMUS Northern Campus]; *Julio César Rincón Martínez*, Universidad Autónoma de Baja California [Autonomous University of Baja California]; *Carla Figueroa Villamar*, Universidad Metropolitana-Azcapotzalco; *Anahí Acevedo Solís y Gamael Santana Gaytán*, Universidad de Colima [University of Colima]; *Maella Minaksi González Cetz*, PIDA (Programa Interinstitucional de Doctorado) [Inter-institutional Doctorate Program]; *Armando Nuñez de Anda*

Special thanks to Michael Humphreys from Oxford-Brookes University, who is one of the thermal comfort studies pioneers, for his effective and wise advice during the statistical analysis process for the present project.

References

ANSI/ASHRAE 55-2013: Thermal Environmental Conditions for Human Ocupancy. Atlanta, 2013.

Bedford, T. (1936). The warmth factor in comfort at work: a physiological study or heating and ventilation (Report núm. 76 HMSO). Great Britain: Industrial Health Board.

Brager, G., & de Dear, R. (2000). A Standard for Natural Ventilation. ASHRAE Journal.

EN (2007). Standard EN15251: Indoor Environmental Parameters for Design and Assessment of Energy Performance of Buildings: Addressing indoor air quality, thermal environment, lighting and acoustics. Brussels. Comité Européen de Normalisation. .

de Dear, R., & Brager, G. (1998). Developing an Adaptive Model of Thermal Comfort and Preference. ASHRAE.

de Dear, R., Brager, G., & Cooper, D. (1997). Developing an Adaptative Model of Thermal Comfort an Preference. Final Report on RP-884. Australia, USA: Macquarie Research Ltd. Macquarie University / Center for Environmental Desing Research, University of California Berkeley.

DOF (15 de 08 de 2012). Parámetros de Estimación de Vida Útil. Diario Oficial de la Federación.

Griffiths, I. (s.f. circa 1990). Thermal comfort in buildings with passive solar features: field studies. Report to the Comission of the European Communities ENS3S-090-UK, Department of Psychology. University of Surrey, Guildford.

Humphreys, M. (1975). Field studies of thermal comfort compared and applied. Symposium on Physiological requirements of the microclimate. Prage: Building Research Establishment, 1-29.

Humphreys, M.A. (1978). Outdoor temperatures and comfort indoors. Building Research and Practice, 92-105.

Humphreys, M. (20, 28 de 06 de 2017). Prelimary Results. Oxford OX3 0B, United Kingdom.

Humphreys, M., Rijal, H., & Nicol, J. (2013). Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. Building and Environment.

Humphreys, M., Nicol, F., & Roaf, S. (2016). Adaptive Thermal Confort. Foundations and Analysis. London and New York: Routledge, 49-53, 296-317.

IEA (2013). World Energy Outlook. Paris, France: International Energy Agency.

IPCC. (2014). Climate Change 2014: Mitigation of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: Contribution of WorkingGroup III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

ISO. (2005). Standard 7730: Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal confort.

Nicol, F. (1993). Thermal Comfort. A handbook for field studies towards an adaptative model. London: University of East London.

Nicol, F. (2004). Adaptative thermal comfort standards in the hot-humid tropics. Energy and Buildings, 628-637.

Nicol, J., & McCartney, K. (2001). Final Report (Public) Smart Controls and Thermal Comfort (SCAT's). Report to the European Commission of the Smart Controls and Thermal Comfort Project. Oxford: Oxford Brooks University.

OECD/IEA. (2015). Energy and Climate Change. World Energy Outlook Special Report. Paris, France: IEA International Energy Agency.

Sanyogita, M., Shukla, Y., Rawal, R., Thomas, L., & de Dear, R. (2016). Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). Building and Environment 98, 55–70.

Appendix A: Measuring Instruments Characteristics

Table A1. Measuring instruments characteristics

Type and model of the measuring instrument	Variables	Measuring range	Accuracy	Response time
QUES Temp 36 with omnidirectional anemometer	WBT	-0 °C to 100 °C	± 0.5 °C	10 min
	DBT	-0 °C to 100 °C	± 0.5 °C	10 min
	WBGT	-0 °C to 100 °C	± 0.5 °C	10 min
	RH	0 to 100 %	± 5 %	10 min
	v	0 to 20 m/s	± 5.0 %	10 min
QUES Temp 36 with omnidirectional anemometer	WBT	-0 °C to 100 °C	± 0.5 °C	10 min
	DBT	-0 °C to 100 °C	± 0.5 °C	10 min
	WBGT	-0 °C to 100 °C	± 0.5 °C	10 min
	RH	0 to 100 %	± 5 %	10 min
Air Probe Accessory	v	0 to 20 m/s	± (0.5 m/s +4 %)	10 min
HOBO U23-001 Pro v	WBT Out.	-40 to 70 °C	± 0.2 °C (0 to 50 °C)	15 min.
	RH Out.	0 to 100 % RH	± 0.2.5 % (10 to 90%)	1 min.
QUES Temp 32 with omnidirectional anemometer	WBT	-0 °C to 100 °C	± 0.5 °C	10 min
	DBT	-0 °C to 100 °C	± 0.5 °C	10 min
	WBGT	-0 °C to 100 °C	± 0.5 °C	10 min
	RH	0 to 100 %	± 5 %	10 min
Mca. Kestrel, mod. 4 200	RH	5 to 95 %	± 3,0 %	20 min
	v		± 0.1 m/s	20 min
QUES Temp 36 with omnidirectional anemometer	WBT	-0 °C to 100 °C	± 0.5 °C	10 min
	DBT	-0 °C to 100 °C	± 0.5 °C	10 min
	WBGT	-0 °C to 100 °C	± 0.5 °C	10 min
	RH	0 to 100 %	± 5 %	10 min
Anemometrer Delta OHM DO 9847	v	0 to 40 m/s	±0.05m/s (0 to 0.99m/s) ± 0.02 m/s (1 V 9.99 m/s)	10 min

Table A2. Measuring instruments characteristics sources

Instruments	Consulted manual	Reference source
QUESTemp 36	QUESTemp 36. Monitor de Estrés Térmico Con almacenaje de datos. Manual de Operación y Servicios.	www.grupomeyer.com.mx
HOBO U23-001 Pro v	U23-001 Data Logger is for use in Outdoor environments	www.microdaq.com
QUESTemp 32	QUEST Temp° 3X Series	www.Quest-Technologies.com
Kestrel 4200 Pocket Air FlowTracker	Manual de instrucciones del Kestrel 4200.	www.KestrelWeather.com
Delta OHM DO 9847	Delta OHM DO 9847. Instrumento multifunción portable datalogger.	www.deltaohm.com

SESSION 5

Schools and Homes

Invited Chairs:
Gary Raw and
Azadeh Montazami

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Adaptive Behaviours and Occupancy Patterns in UK Primary Schools: Impacts on Comfort and Indoor Quality

Sepideh Sadat Korsavi[1], Azadeh Montazami[2]

[1] PhD Student, Centre for the Built and Natural Environment (BNE), Coventry University, UK, korsavis@uni.coventry.ac.uk
[2] Research Fellow, Centre for the Built and Natural Environment (BNE), Coventry University, UK, azadeh.montazami@coventry.ac.uk

Abstract: To improve the quality of school environment and reach state of comfort, it's important that teachers and students take appropriate personal and environmental adaptive behaviours. Studies on adaptive behaviours are mainly focused on adults, especially in residential and office buildings while children's adaptive behaviours at schools are not largely studied. This paper has investigated adaptive behaviours, influential factors and their impact on comfort and indoor quality by doing field studies in 4 primary schools and 15 classrooms in Coventry, UK during July, September, October and November 2017 through observations, subjective and objective measurements. The results are derived from observations on around 400 students aged 9-11 and from more than 600 surveys. Results illustrate that students usually take personal adaptive behaviours after or before breaks, and the number of these behaviours increases during warmer seasons and in afternoon sessions. Students' decisions over appropriate clothing level is related to time of year, however, 27% of students could improve their thermal vote by taking off or taking on jumpers/cardigans. Some environmental adaptive behaviours like door operation are less related to climatic factors, however, window operation is correlated to indoor temperature (R^2=0.29) and outdoor temperature (R^2=0.35). Observations show that around 80% of all environmental adaptive behaviours are done by teachers, teacher assistants or on their request, which can provide conditions that are not comfortable for children. Therefore, it is important to facilitate adaptive behaviour of children to improve their comfort level.

Keywords: Adaptive Behaviors, Comfort, Indoor Quality, Children, Schools

1. Introduction

According to the adaptive approach by Nicol & Humphreys (2002) , "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort". From the biological perspective, occupants interact with the environment to secure and restore their comfort if appropriate opportunity is provided (Humphreys and Nicol, 1998). Two forms of adaptive behaviours introduced by Nicol et al. (2004) are those which help occupants to feel comfortable in the present situation like removing a jacket or changing postures, called personal behaviours, and those which are taken to make the environment comfortable for the subjects like controlling windows or shadings, called environmental behaviours.

Adaptive behaviours are influenced by climatic factors like temperature, wind speed, air movement, humidity, solar intensity and CO_2 concentration (Humphreys and Nicol, 1998; Nicol, Humphreys and Olesen, 2004; Fabi *et al.*, 2012). The study by Fabi et al. (2012) has suggested other drivers than climatic factors for occupants' behaviour including contextual (e.g., building properties, orientation, heating and ventilation type, season, occupancy patterns and time of day), psychological (expectations, habits, perception, financial and environmental concerns and lifestyle), physiological (age, gender, clothing, activity level, food or beverage intake) and social (occupants' interactions for determining adaptive action).

Occupancy patterns include proximity to the control, the number of occupants sharing a control or type of space (private or shared), arrival and departure patterns or occupancy intervals (just after arrival, intermediate, just before departure) (Gunay, O'Brien and Beausoleil-Morrison, 2013; O'Brien and Gunay, 2014). The study by O'Brien and Gunay (2014) has also identified other contextual factors including availability of controls, accessibility of controls, complexity and transparency of automation systems, presence of mechanical/electrical systems, view and connection with outside, interior design, experience and foreseeable future conditions, visibility of energy use and social constraints (O'Brien and Gunay, 2014). The study by (Humphreys and Nicol, 1998) has discussed circumstances that restrict adaptive actions which are culture, affluence, working conditions, comfort operated by another occupant, conflicting requirements, personality, fashion and health.

To reach comfort and improve environment's quality, many studies have refered to the role of adaptive behaviours (Raja *et al.*, 2001; Nicol and Humphreys, 2002; Rijal *et al.*, 2007; Herkel, Knapp and Pfafferott, 2008; Fabi *et al.*, 2012; Nicol, Humphreys and Roaf, 2012; Gunay, O'Brien and Beausoleil-Morrison, 2013) and its effect on occupants' forgiveness and satisfaction (Baker and Standeven, 1997; Leaman and Bordass, 1999, 2007; Humphreys, 2005; Nicol and Roaf, 2005; Roulet *et al.*, 2006; Frontczak and Wargocki, 2011). According to Dubrul (1988), behaviours are stongly related to comfort perception. Occupants who have the possibility to control their environment, suffer from fewer building related symptoms (Paciuk, 1990; Brager, Paliaga and Dear, 2004; Toftum, Andersen and Jensen, 2009), can tolerate higher temperatures (Brager, Paliaga and Dear, 2004) and discomfort is reported less by them (Raja *et al.*, 2001).

Personal and environmental adaptive behaviors and operation of controls can directly or indirectly affect students' comfort in educational buildings and are related to several factors.

On personal behaviours in educational buildings, studies have shown that students' clothing level usually follows sequence of temperature, running mean temperature and long term fluctuation in temperature (Nicol and Humphreys, 1973; Humphreys, 1974, 1977). Study by Humphreys (1974) shows that clothing level depends on the room temperature; optimum temperature for students with light clothing occurs at 24.5^{o}C, for students with heavy clothing occurs at 21.5^{o}C and for students with winter clothing occurs at 18.5^{o}C (Humphreys, 1974). Humphreys (1977) shows that the effect of temperature changes during day on discomfort was more than its effect on clothing level. On activity type, the study by Raja and Nicol (1997) shows that within the freedom students have for type of activity, more open activities are preferred as temperature increases more.

On environmental adaptive behaviors in educational buildings, studies have shown that window operation is influenced by outdoor temperature (Dutton and Shao, 2010; Stazi, Naspi and D'Orazio, 2017), indoor temperature (Santamouris *et al.*, 2008; Stazi, Naspi and D'Orazio, 2017), humidity (Dutton and Shao, 2010), CO_2 level (Dutton and Shao, 2010), time of day (Stazi, Naspi and D'Orazio, 2017) and noise level (Montazami, Wilson and Nicol, 2012). Blinds are operated to avoid glare or sunlight (Theodorson, 2009; Montazami and Gaterell, 2014), prevent overheating (Montazami and Gaterell, 2014), limit outside distractions (Montazami and Gaterell, 2014), provide outside views (Sanati and Utzinger, 2013) and to darken the room for presentations (Theodorson, 2009). Blinds' ease of use (Sze, 2009; Sanati and Utzinger, 2013) and window design (Sanati and Utzinger, 2013) also affect the operation of blinds.

To provide indoor environment quality in schools and reach state of comfort, it's important that children and teachers take appropriate adaptive behaviours and the chance to exercise those adaptive behaviours should be provided for them. Therefore, the main objectives of the paper are as follows:

- To investigate what factors affect adaptive behaviours of primary school children and how these factors affect students' practice
- To examine the effect of adaptive behaviours and occupancy patterns on environmental variables and state of comfort

2. Methodology

Field studies were carried out in 4 primary schools and 15 classrooms in West Midlands, UK during July, September, October and November 2017, consisting of objective measurements, subjective measurements and observations.

2.1. Climate and weather during data collection

The investigated primary schools are located in Coventry which is the second largest city in the West Midlands region. During the field study time from 17 July to 24 November, highest and lowest average outdoor temperature for occupancy pattern of primary school children were recorded 23^{0}C in July/18 and 6.15^{0}C in November/24, respectively, as shown in Fig 1. Field studies were conducted in a wide range of outdoor temperature from 2.3^{0}C in November/24 to 24.9^{0}C in July/18. During the time field studies were conducted, relative humidity changed from 50-85% in July, from 81-92% in September and from 75-90% in October and November, with one rainy day in July, two rainy days in September and no rainy days in October and November. Outdoor variables were collected from local stations (Weather Observations Website, 2017).

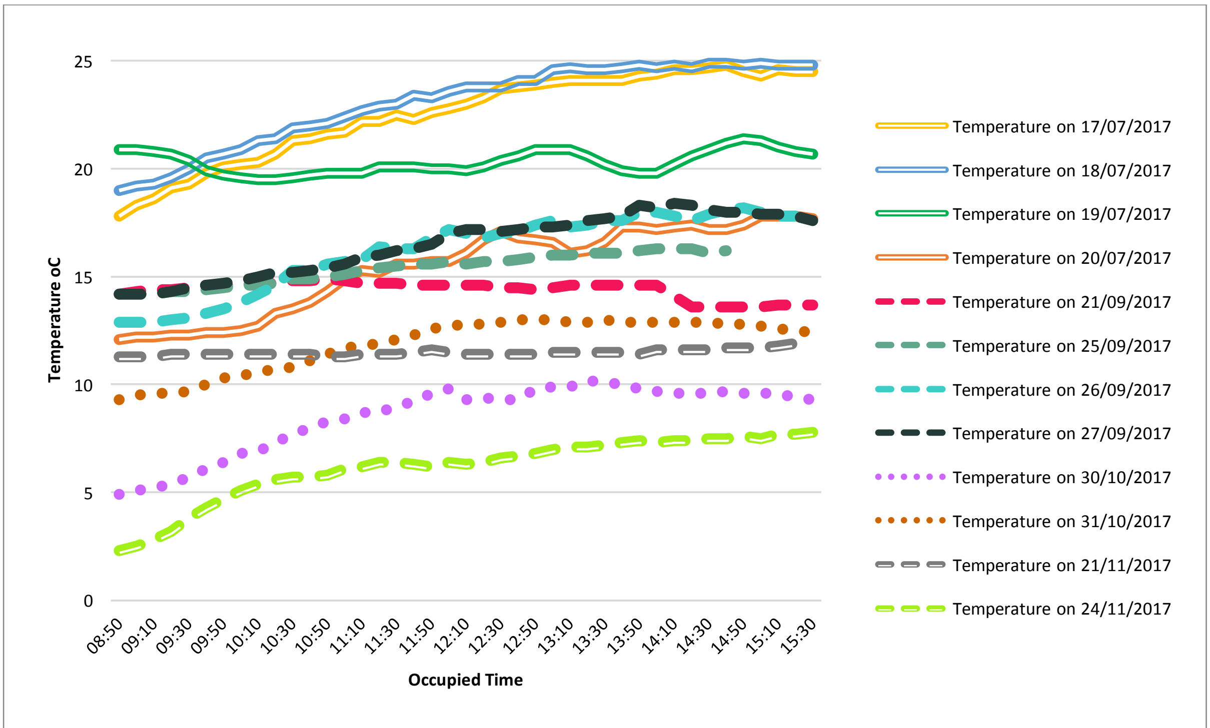


Figure **1**. Outdoor temperature of Coventry during occupied time of field study, retrieved from (Weather Observations Website, 2017)

Table 1. An overview of architectural features of classrooms and controls

School & Class Number	Date	Classroom Orientation	Floor	Area (m^2)	Area of Operable Windows (m^2)	Area of Non-operable Windows (m^2)	Area of door Glazing (m^2)	Total Area of Glazing (m^2)	Number of Operable Windows	Type of Window Operation	Min Height of Operable Window Sill (m)	Exterior Door
S1, C1	17/07/2007	North East	First Floor	60	8	0	0	8	8	Manual	1	No
S1, C2	18/07/2017	South West	First Floor	60	8	0	0	8	8	Manual	1	No
S1, C3	19/07/2017	South West	First Floor	60	8	0	0	8	8	Manual	1	No
S1, C4	20/07/2017	South West	First Floor	60	8	0	0	8	8	Manual	1	No
S1, C5	21/07/2017	North East	First Floor	60	8	0	0	8	8	Manual	1	No
S2, C6	21/09/2017	North West	First Floor	60	8	0	0	8	8	Manual	1	No
S2, C7	25/09/2017	South East	First Floor	60	8	0	0	8	8	Manual	1	No
S2, C8	26/09/2017	South East	First Floor	60	8	0	0	8	8	Manual	1	No
S2, C9	27/09/2017	North West	First Floor	60	8	0	0	8	8	Manual	1	No
S3, C10	30/10/2017	South and West	Ground Floor	65	2.2	8	0	9	6	Manual	1.6	Yes
S3, C11	31/10/2017	South and Northwest	Ground Floor	65	2.2	8	0	9	6	Manual	1.6	No
S3, C12	01/11/2017	North West	First Floor	60	2.5	4	0	6.5	5	Manual with a handle	2.6	No
S4, C13	21/11/2017	West	Ground Floor	45	0.5	0.8	1	2.3	2	Manual	1.8	Yes
S4, C14	22/11/2017	West	Ground Floor	60	0.5	0.8	1	2.3	2	Manual	1.8	Yes
S4, C15	24/11/2017	No window	Ground Floor	60	0	0	1	2.3	0	Manual	1.8	No

Table 2. Several photos of classrooms and windows, Photos by Sepideh Korsavi

S1, C1- S2, C9	S3, C10	S3, C11	S3, C12	S4, C13-C14
				

2.2. Buildings Description

The investigated primary schools are all two-story naturally ventilated buildings with classrooms in different designs and orientations as the study aims to find out how architectural feature affect students' adaptive behaviours. Table 1 shows some architectural features of the classrooms like design of windows play a main role on adaptive behaviours of students. Architectural features of classrooms including their area and orientation, windows' area and characteristics and their type of the operation (i.e. manual or automatic) are listed in Table 1. Controls that can be operated in each classroom include windows, blinds, interior door, exterior door and fan, if any. Several classrooms located in the ground floor might have an exterior door to the playground which is usually operated according to occupancy patterns and on breaks. The only classroom that had cooling fan was Classroom 2 in School 1 and the fan was operated during summer days. Heating systems are operated by caretakers so they are not considered as controls that can be operated in the classroom. Table 2 shows five different window designs, with classrooms 1-9 having the same design; however, classroom 10-14 have different designs and classrooms 15 does not have any window.

2.3. Data acquisition

For the objective of the study, subjective measurements, observations and objective measurements were conducted in 15 classrooms to obtain more reliable data.

2.3.1. Subjective measurements and Observations:

The paper-based survey, which asks about 'personal adaptive behaviours like change in clothing level, fanning and drinking', thermal sensation and preference, comfort and tiredness, is designed for 9-11 years old students (year 5 and year 6) who can read and write easily. More than 600 questionnaires were collected from morning and afternoon sessions, with students filling out surveys once at the end of morning session and once at the end of afternoon session. The design of the study defines transverse sampling in which bias is lowered or avoided, thus, the results are more representative.

Through observations, each student was given a reference number which made observing and recording adaptive behaviours possible. Personal and environmental adaptive behaviours of around 400 students were observed and recorded in a logbook. The results derived from these observations help to verify surveys' results as reference numbers were written on top of each survey. Table 1 provides an overview of the number of students and the number of collected surveys in each school.

Table 3. An overview of the number of students and collected surveys

School Number	Date	Number of observed students	Number of collected surveys during morning and afternoon sessions
School 1	17-21 July 2017	130	200
School 2	21-27 September 2017	110	195
School 3	29-31 October 2017	65	115
School 4	21-24 November 2017	85	115

2.3.2. Objective measurements

Environmental variables like air temperature, radiant temperature, humidity, air speed and CO_2 level were measured at 5-minute intervals by multi-purpose SWEMA 3000, temperature, humidity and Tiny Tag CO2-TGE-0011 data loggers. State of windows, blinds and doors was also recorded by time-lapse cameras at 5 minute intervals.

3. Results

3.1. Personal Adaptive Behaviours

Results of surveys and observations show that personal adaptive behaviours are correlated with occupancy patterns, type of activity, season, outdoor temperature and time of day. However, the time that personal adaptive behaviours happens is more related to occupancy patterns and type of activity, and the frequency and number of those personal behaviours are more related to season, outdoor temperature and time of day, Fig 2 & 3.

Students usually take personal adaptive behaviours like drinking water, fanning and changing clothing level right after or before breaks, especially after breaks, physical Education (PE) and lunch, and that is why the percent of students taking personal adaptive behaviours increases during day, Fig 2 & 3. Percent of students drinking increases up to 92% in July and up to 33% in October. Percent of students fanning increases up to 48% in July and up to 7% in October. Percent of students without jumper increases up to 100% in July and up to 40% in October. According to the results of these two months, percent of students changing clothing level is higher than percent of students drinking and fanning. Among all personal adaptive behaviours, changing seats and fanning are the less frequent ones. Each student is allocated a fixed seat and students can only change seats with teacher's permission and according to type of activity. Fanning was rarely observed in October (7%), however it was more frequent in July (48%). Another personal adaptive behaviour, which was observed in the presence of glare in eyes or on TV, was changing posture or seating direction. According to the above statistics, percentage of personal adaptive behaviours is higher in July than in October which can be attributed to outdoor and indoor temperature and time of year. The pattern of taking personal behaviours is almost similar, however, their frequency is different in different seasons.

Less personal behaviours were observed during teaching activities which is mainly due to the fact that students are not free to move around in the classroom to drink or change seats, Fig 2 & 3. Several other studies (Santamouris *et al.*, 2008; Stazi, Naspi and D'Orazio, 2017) show that less adaptive behaviors are taken during teaching activities than during breaks as pupils are concentrating on lessons. Students' freedom to change clothing level, seating position and posture is higher in art classes which can help provide a more comfortable environment for them as the study by Nicol & Humphreys (1973) in educational buildings in UK has shown that students can make a more comfortable environment for themselves by changing posture and activity.

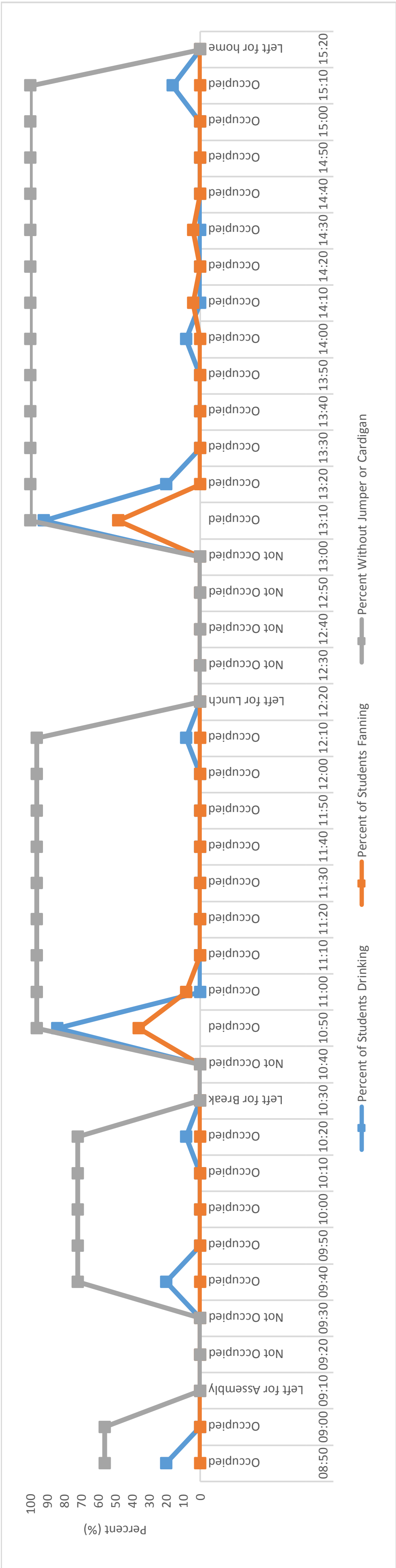


Figure **2.** Percent of students drinking, fanning and without jumper in a single day in July

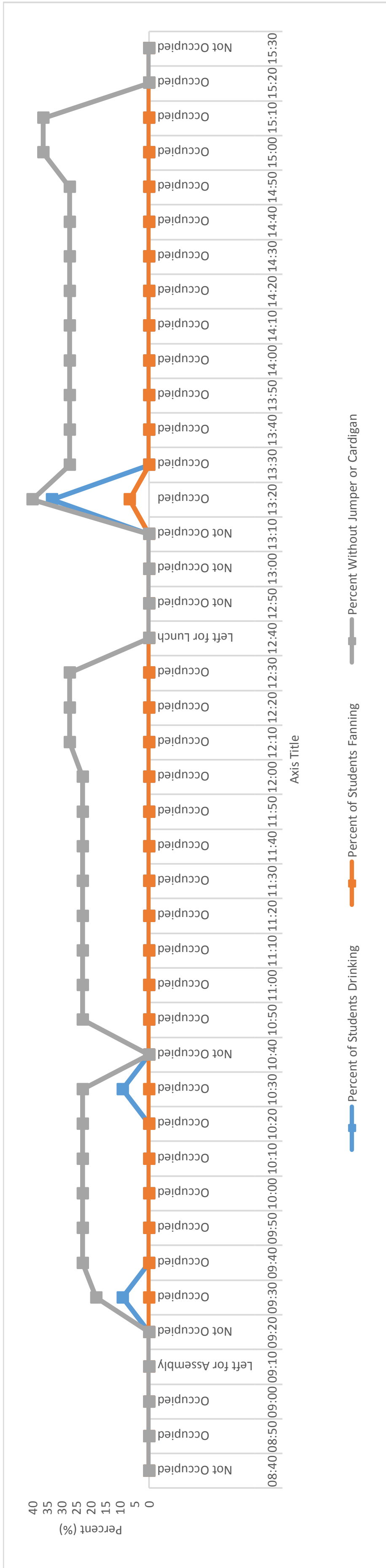
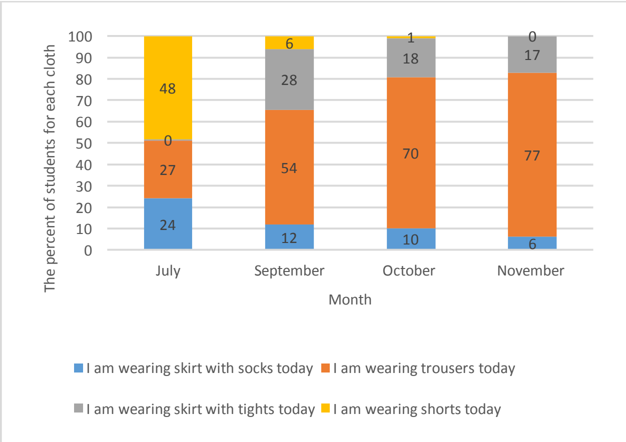


Figure 3. Percent of students drinking, fanning and without jumper in a single day in October

3.1.1. Clothing Level and Comfort Vote

Students' decisions on what to wear mostly depend on time of year, as shown in Fig 4 & 5. Fig 4 shows that most students wear shorts in July (48%), however, girls and boys mostly wear trousers in October and November, 70% and 77%, respectively. The percent of girls wearing skirt with socks decreases from July to November and the percent of students wearing skirt with tights increases from July (24%) to September (12%) and then decreases again from September to October (10%) and November (6%); girls start to wear more trousers in these two months. This adaptive behaviour which starts even before getting to school shows students' perception of outdoor temperature and seasons. Results show that 94 students do not even take their jumper/cardigan to school in July and this number decreases in other months, as shown in Fig 5. Several other studies have already shown that students' clothing level usually follows sequence of temperature, running mean temperature and long term fluctuation in temperature (Nicol and Humphreys, 1973; Humphreys, 1974, 1977).



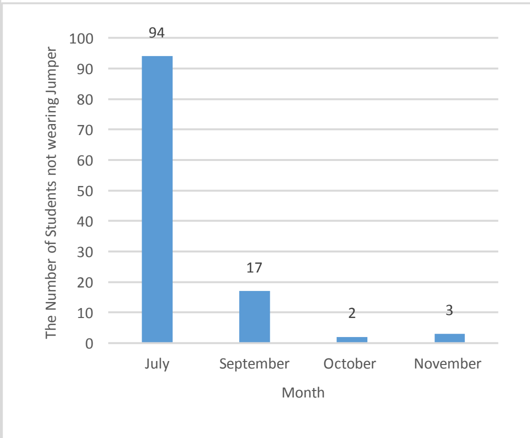


Figure 4. Students' decision on clothing. Fig 5. The number of students not wearing jumper/cardigan in different seasons

Results of the surveys show that 27% of students could improve their thermal preference vote by putting on or off jumper/cardigan. Indeed, 17% of students preferred a cooler and colder environment and had jumpers or cardigans on, as shown in Fig 6. Similarly, 10% students preferred warmer and hotter environment and did not have jumper/cardigans on, as shown in Fig 6. Similarly, The study by Nicol & Humphreys (1973) on educational buildings in UK shows that constraints on clothing at schools can cause discomfort equivalent to a departure of 4°C from the optimum temperature (Nicol and Humphreys, 1973).

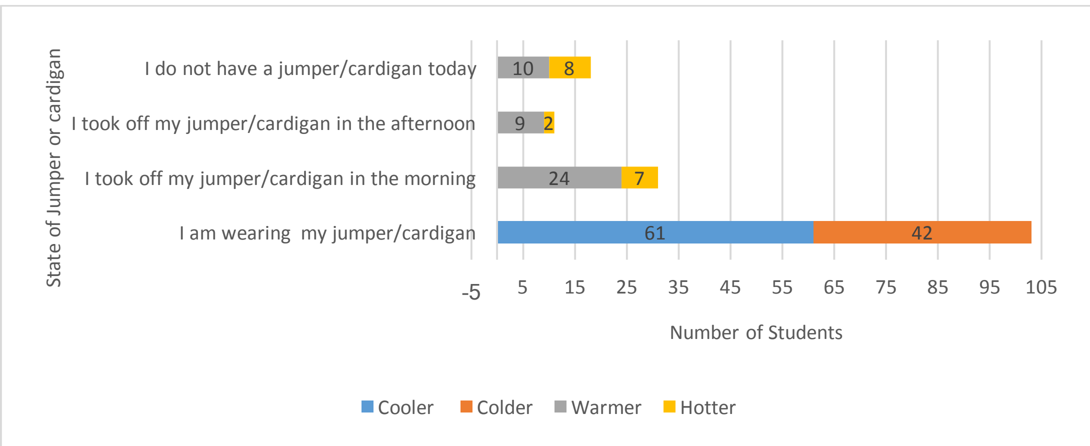


Figure 6. The number of students who could improve their thermal state by taking on or off jumper/cardigan

3.2. Environmental Adaptive Behaviours

3.2.1. Who does operations?

Observations show that around 80% of all operations are done by teachers, teacher assistants or on teachers' request and less than 20% are done by students or on students' request, as shown in Fig 7. Therefore, there is a risk that environmental conditions are mainly adjusted based on teachers' perceptions and preferences, and consequently classrooms' conditions might not suit the state of comfort of students. Results of the observation show that those students who decide to do environmental adaptive behaviours or are asked to do environmental behaviours, are usually seating close to the means of controls, either door, window or blind.

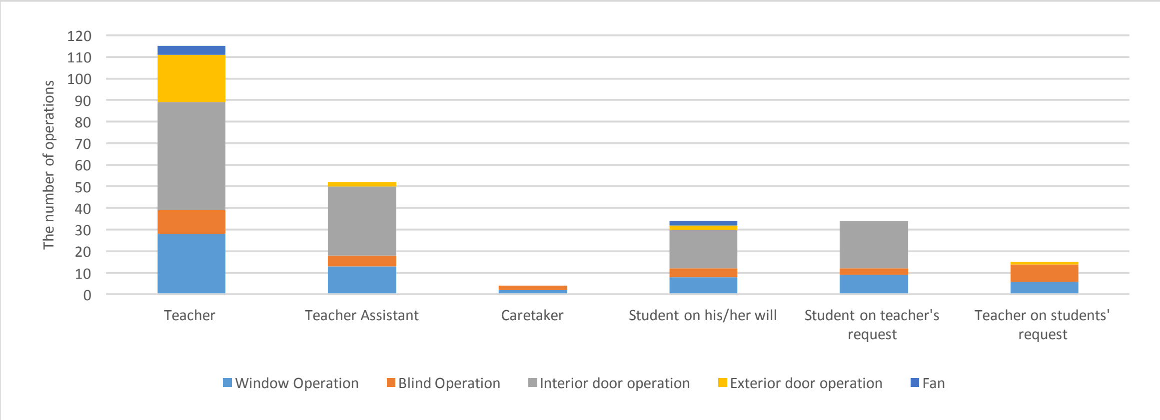
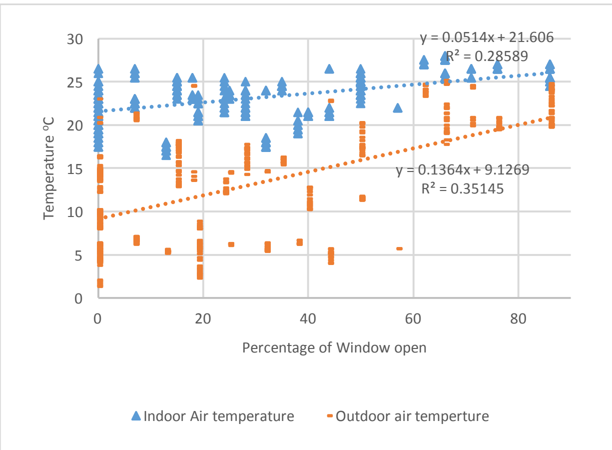


Figure 7. Who has operated different controls?

3.2.2. What factors affect operations?

The results of the study show that the percentage of open window is related to indoor temperature (R^2=0.29) and outdoor temperature (R^2=0.35), as shown in Fig 8. Similarly, the number of window adjustment is correlated with indoor temperature (R^2=0.24) and outdoor temperature (R^2=0.33), Fig 9. These results are supported by the evidence available in literature reviews (Dutton and Shao, 2010; Stazi, Naspi and D'Orazio, 2017) (Santamouris *et al.*, 2008; Stazi, Naspi and D'Orazio, 2017). In addition, this study shows that operation of openings (i.e. windows and doors) is not only affected by climatic factors and it is also affected by occupancy patterns and background noise level.



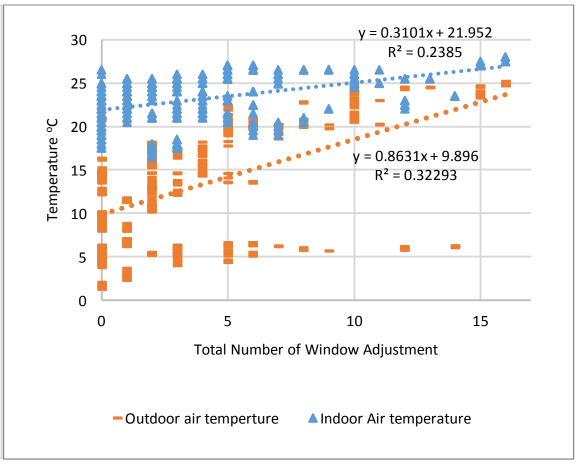


Figure 8. The relation between percentage of open window and indoor & outdoor temperature. Figure **9**. The relation between the number of window adjustment and indoor & outdoor temperature

3.2.3. How do operations and occupancy patterns affect environmental variables?

Providing an opportunity for students to practice adaptive behaviours in classrooms is important as all personal and environmental adaptive behaviours, students' occupancy patterns and the number of them can affect climatic variables and their state of comfort. Fig 10 shows an example of how operation of controls and occupancy patterns can affect environmental variables in a single day in summer. Not only opening windows and door affects temperature and indoor air quality, the number of students and their type of activity also affects these variables. A noticeable difference can be seen at 9:30 and 10:00 when the number of students increased from 28 to 53 for practicing singing. By an increase in the number of students and change in their type of activity, radiant temperature increased more than two degrees (from 24.6 at 9:00 to 26.8 at 10:00) and CO_2 level increased up to around four times (from 658 ppm at 9:00 to 2331 ppm at 10:00). The state of windows, type of activity and the number of students do not change from 9:30 to 10:00, yet, radiant temperature, air temperature and CO_2 level increase which can be attributed to door being closed and the longer period that the activity is taking place, Fig 10. At 10:30, when more windows were left open and students left the classroom, radiant temperature dropped three degrees (3^oC) and CO_2 level decreased to around four times, Fig 10. The state of windows at different times by time lapse camera and the percentage of window open is presented in Table 4.

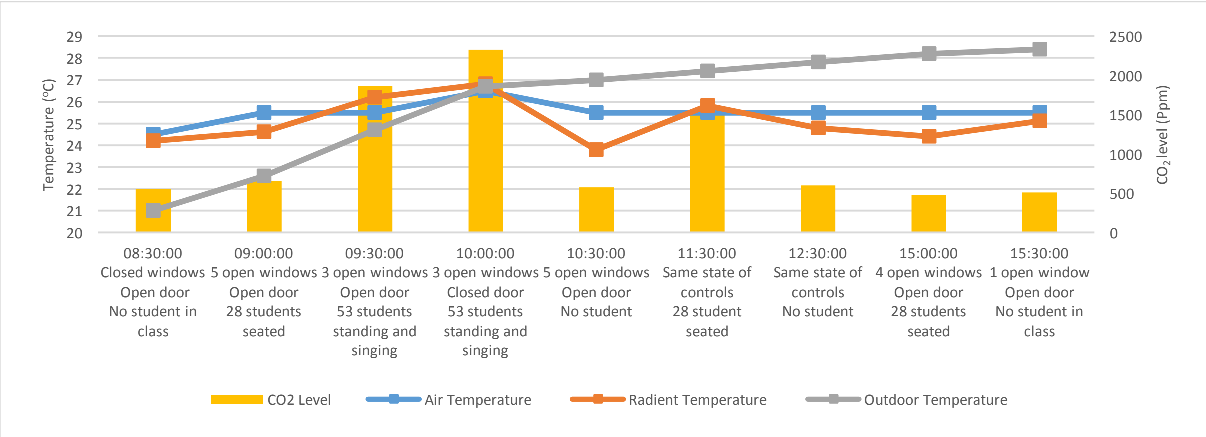
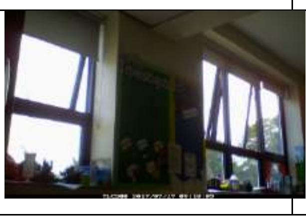


Figure 10. The effect of state of controls and occupancy patterns on environmental variables

Table 4. State of windows at different times in the classroom, Photos by Time-lapse cameras

Time	**08:30**	**09:00**	**09:30**
Open window (%)	**0%**	**66%**	**50%**
State of windows			
Time	**10:00**	**10:30**	**15:30**
Open window (%)	**50%**	**86%**	**18%**
State of windows			

3.2.4. How to facilitate adaptive behaviours for children?

To provide appropriate opportunities for students to operate controls and according to their own preference, controls especially windows and blinds should be carefully designed. Students in [S3, C10], [S3, C12], [S4, C13] and [S4, C14] do not have an opportunity to operate windows and blinds due to their design and type of access to them, Table 2. In [S3, C10], [S4, C13] and [S4, C14], small windows can only be operated by teacher or teacher assistant as the height of window sill is 1.6-1.8 (m) and they are out of reach of students, Table 1.

Moreover, windows are located at the end of the classroom and next to teacher's desk, which makes children's access to them difficult, 2^{nd} and 5^{th} photo in Table 2. In [S3, C12], access to windows is not difficult, however, windows at the height of students are not operable. Therefore, only upper windows are operated by a handle which is done by teacher or teacher assistant, Table 2. The interaction of students with windows and blinds was observed more frequently in classrooms 1-9 in schools 1 & 2 since windows were different in design and size, lower in height (the height of window sill is 1m) and easy to access. Two more studies in educational buildings have shown that blinds' ease of use and window design affect the frequency of blind operation (Sze, 2009; Sanati and Utzinger, 2013).

4. Conclusion

Adaptive behaviours of around 400 students aged 9-11 were studied in four UK primary schools. The study was carried out during July, September, October and November 2017 through observational field studies, subjective and objective measurements and more than 600 questionnaires were collected.

Results reveal that the time that personal adaptive behaviours takes place is more related to occupancy patterns and type of activity, however, the frequency of personal adaptive behaviours is more related to season, outdoor temperature and time of day. Personal adaptive behaviours like drinking water, fanning and taking off or on jumper/cardigan usually happens right after and before breaks, especially after breaks, Physical Education (PE) and lunch with fewer personal behaviours during teaching activities. Percent of students displaying personal adaptive behaviours is higher in summer than in autumn which can be attributed to outdoor and indoor temperature. Students' decisions over clothing mostly depends on time of year, with boys wearing more shorts and girls wearing more 'skirts with socks' in July; however, both girls and boys wear more trousers in October and November. Many students do not take their jumpers/cardigans when outdoor temperature is warmer. Surveys' results show that 27% of students could improve their thermal preference vote by taking off or taking on jumpers/cardigans.

On environmental adaptive behaviours, the operation of some of them like doors is less related to climatic factors, however, operation of windows is correlated with indoor temperature (R^2=0.29) and outdoor temperature (R^2=0.35). Around 80% of all operations are done by teachers, teacher assistants or on their request, therefore, provided environmental conditions can be inappropriate according to students' state of comfort. It is important that design of controls facilitate adaptive behaviours of children according to their physiology. Easy to access and easy to operate controls that are safe for children can help them practice adaptive behaviours. Adaptive behaviours and occupancy patterns influence environmental variables, so it is important to consider the extent to which students can practice adaptive behaviours, their arrival and departure patterns, the number of them in the classroom and their type of activities.

5. References

aker, N. and Standeven, M. (1997) 'A Behavioural Approach To Thermal Comfort Assessment', *International Journal of Solar Energy*, 19(1–3), pp. 21–35. doi: 10.1080/01425919708914329.

Brager, G. S., Paliaga, G. and Dear, R. de (2004) 'Operable Windows , Personal Control , and Occupant Comfort', *ASHRAE Transactions 2004*, 110(2), pp. 17–35.

Dubrul, C. (1988) *Inhabitant Behaviour with Respect to Ventilation - A Summary Report of IEA Annex VIII*, *AIVC Technical Reports*. Available at: http://www.aivc.org/Publications/publications.html#Technicalreports%255Cnhttp://www.aivc.org/Subscriptions/aivc_subscriptions.htm.

Dutton, S. and Shao, L. (2010) 'Window opening behaviour in a naturally ventilated school', *Proceedings of the 4th National Conference of IBPSA- …*, (Dutton 2009), pp. 260–268. Available at: http://www.ibpsa.us/pub/simbuild2010/papers/SB10-DOC-TS05B-02-Dutton.pdf.

Fabi, V. *et al.* (2012) 'Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models', *Building and Environment*. Elsevier Ltd, 58, pp. 188–198. doi: 10.1016/j.buildenv.2012.07.009.

Frontczak, M. and Wargocki, P. (2011) 'Literature survey on how different factors influence human comfort in indoor environments', *Building and Environment*. Elsevier Ltd, 46(4), pp. 922–937. doi: 10.1016/j.buildenv.2010.10.021.

Gunay, H. B., O'Brien, W. and Beausoleil-Morrison, I. (2013) 'A critical review of observation studies, modeling, and simulation of adaptive occupant behaviors in offices', *Building and Environment*. Elsevier Ltd, 70, pp. 31–47. doi: 10.1016/j.buildenv.2013.07.020.

Herkel, S., Knapp, U. and Pfafferott, J. (2008) 'Towards a model of user behaviour regarding the manual control of windows in office buildings', *Building and Environment*, 43(4), pp. 588–600. doi: 10.1016/j.buildenv.2006.06.031.

Humphreys, M. A. (1974) 'Classroom Temperature, Clothing and Thermal Comfort--A Study of Secondary School Children in Summertime', *Reprinted from The Building Services Engineer (JIHVE)*, 41, pp. 191–202.

Humphreys, M. A. (1977) 'A study of the thermal comfort of primary school chilrdren in summer', *Building and Environment*, 12, pp. 231–239.

Humphreys, M. A. (2005) 'Quantifying occupant comfort: are combined indices of the indoor environment practicable?', *Building Research & Information*, 33(4), pp. 317–325. doi: 10.1080/09613210500161950.

Humphreys, M. A. and Nicol, J. F. (1998) 'Understanding the adaptive approach to thermal comfort', in *ASHRAE Transactions*, pp. 991–1004.

Leaman, A. and Bordass, B. (1999) 'Productivity in buildings: the "killer" variables', *Building Research & Information*, 27(1), pp. 4–19. doi: 10.1080/096132199369615.

Leaman, A. and Bordass, B. (2007) 'Are users more tolerant of "green" buildings?', *Building Research & Information*, 35(6), pp. 662–673. doi: 10.1080/09613210701529518.

Montazami, A. and Gaterell, M. (2014) 'Occupants' behaviours in controlling blind s in UK primary schools', *Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a changing world Cumberland*, (April), pp. 10–13.

Montazami, A., Wilson, M. and Nicol, F. (2012) 'Aircraft noise, overheating and poor air quality in classrooms in London primary schools', *Building and Environment*. Elsevier Ltd, 52, pp. 129–141. doi: 10.1016/j.buildenv.2011.11.019.

Nicol, F., Humphreys, M. and Roaf, S. (2012) *Adaptive thermal comfort: principles and practice*. Available at: https://books.google.co.uk/books?hl=en&lr=&id=vE7FBQAAQBAJ&oi=fnd&pg=PT17&dq=Adaptive+thermal+comfort+:+principles+and+practice&ots=ogsYgsSAnU&sig=ttYfYOEM8-tlT-biIF7Hjb68n3c (Accessed: 3 November 2016).

Nicol, F. and Roaf, S. (2005) 'Post-occupancy evaluation and field studies of thermal comfort', *Building Research & Information*, 33(4), pp. 338–346. doi: 10.1080/09613210500161885.

Nicol, J. F. and Humphreys, M. A. (1973) 'Thermal comfort as part of a self-regulating system', *Building Research and Practice*, 1(3), pp. 174–179. doi: 10.1080/09613217308550237.

Nicol, J. F. and Humphreys, M. A. (2002) 'Adaptive thermal comfort and sustainable thermal standards for buildings', *Energy and Buildings*, 34(6), pp. 563–572. doi: 10.1016/S0378-7788(02)00006-3.

Nicol, J. F., Humphreys, M. A. and Olesen, B. (2004) 'A stochastic approach to thermal comfort - Occupant behavior and energy use in buildings', *ASHRAE Transactions*, 110 PART I, pp. 554–568.

O'Brien, W. and Gunay, H. B. (2014) 'The contextual factors contributing to occupants' adaptive comfort behaviors in offices - A review and proposed modeling framework', *Building and Environment*. Elsevier Ltd, 77, pp. 77–88. doi: 10.1016/j.buildenv.2014.03.024.

Paciuk, M. (1990) 'The Role of Personal control of the Environment in Thermal Comfort and Satisfaction at the Workplace', *21th Annual Conference of the Environmental Design Research Association*, pp. 303–312.

Raja, I. A. *et al.* (2001) 'Thermal comfort: Use of controls in naturally ventilated buildings', *Energy and Buildings*, 33(3), pp. 235–244. doi: 10.1016/S0378-7788(00)00087-6.

Raja, I. A. and Nicol, F. (1997) 'A technique for recording and analysis of postural changes associated with thermal comfort [Technical note]', *Applied Ergonomics*, 28(3), pp. 221–225. doi: 10.1016/S0003-6870(96)00036-1.

Rijal, H. B. *et al.* (2007) 'Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings', *Energy and Buildings*, 39(7), pp. 823–836. doi: 10.1016/j.enbuild.2007.02.003.

Roulet, C.-A. *et al.* (2006) 'Multicriteria analysis of health, comfort and energy efficiency in buildings', *Building Research & Information*, 34(5), pp. 475–482. doi: 10.1080/09613210600822402.

Sanati, L. and Utzinger, M. (2013) 'The effect of window shading design on occupant use of blinds and electric lighting', *Building and Environment*, 64. doi: 10.1016/j.buildenv.2013.02.013.

Santamouris, M. *et al.* (2008) 'Experimental investigation of the air flow and indoor carbon dioxide concentration in classrooms with intermittent natural ventilation', *Energy and Buildings*, 40(10), pp. 1833–1843. doi: 10.1016/j.enbuild.2008.04.002.

Stazi, F., Naspi, F. and D'Orazio, M. (2017) 'Modelling window status in school classrooms. Results from a case study in Italy', *Building and Environment*, 111, pp. 24–32. doi: 10.1016/j.buildenv.2016.10.013.

Sze, J. L. (2009) 'Indoor Environmental Conditions in New York City Public School Classrooms, a Survey.'

Theodorson, J. (2009) 'Daylit Classrooms at 47N, 117W Insights from occupation', *PLEA2009 - 26th Conference on Passive and Low Energy Architecture*, (June), pp. 22–24.

Toftum, J., Andersen, R. V. and Jensen, K. L. (2009) 'Occupant performance and building energy consumption with different philosophies of determining acceptable thermal conditions', *Building and Environment*, 44(10), pp. 2009–2016. doi: 10.1016/j.buildenv.2009.02.007.

Wang, Y. *et al.* (2015) 'Evaluation on classroom thermal comfort and energy performance of passive school building by optimizing HVAC control systems', *Building and Environment*, 89. doi: 10.1016/j.buildenv.2015.02.023.

Weather Observations Website (2017) *http://wow.metoffice.gov.uk/*. Available at: http://wow.metoffice.gov.uk/ (Accessed: 20 December 2017).

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Thermal Comfort in the UK Higher Educational Buildings: The Influence of Thermal History on Students' Thermal Comfort

Mina Jowkar[1] and Azadeh Montazami[2]

[1] PhD Student, Centre for the Built and Natural Environment (BNE), Coventry University, UK, jowkarm@uni.coventry.ac.uk;
[2] Research Fellow, Centre for the Built and Natural Environment (BNE), Coventry University, UK, azadeh.montazami@coventry.ac.uk

Abstract: Statistics regarding the number of international students in the UK higher educational buildings show an upward trend in the recent years. These students coming from different cultural and climatic backgrounds have various thermal perceptions inside the classrooms. According to the significant influence of thermal quality of learning environments on students' productivity and wellbeing, it is essential to develop specific environmental guidelines for the UK higher educational buildings based on the students' backgrounds. Developed standards not only can provide occupants' thermal comfort in such multicultural spaces, but also can minimize energy consumption and running costs within the higher educational buildings in this country. This study evaluated the students' thermal perception in three different types of learning environments including fifteen Naturally Ventilated lecture rooms, studios and PC Labs from three different buildings of Coventry University. Indoor air temperature, humidity level, air velocity and mean radiant temperature were monitored in different times of a day. A questionnaire survey was conducted on approximately 1000 undergraduate and postgraduate students at the same time of recording operative temperature. This study is completed based on thermal comfort votes of 650 students Results reveal the influence of short and long-term thermal history including climatic background, thermal condition of current accommodation and thermal adaptation to the UK weather on students' thermal comfort perception inside a classroom. The outcome of this study can be applied to develop the reliable and practical guidelines for the multicultural higher educational buildings within the UK.

Keywords: thermal comfort, higher educational buildings, classrooms, climatic background

1. Introduction

Thermal comfort can be defined as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ASHRAE 55, 2004). This clearly shows that people's thermal comfort is a subjective response (Singh, 2015), therefore, an identified value cannot thermally satisfy all the occupants in a space. Occupants' "condition of mind", in terms of thermal comfort, can be different due to various thermal perceptions, expectations, cultures, moods and some other personal or social factors (Katafygiotou and Serghides 2014, Nicol and Humphreys 2002, Singh et al. 2011).

Thermal history and adaptation is one of the major factors affecting people's thermal comfort in an environment. Occupants' thermal sensation in a space resulted from the contrast between the current and previous environmental experiences (Ji et al. 2017, Cândido et al. 2010). In general, the impact of thermal history on thermal comfort can be divided into two main groups of *short- term* and *long- term* based on the occupants' exposure duration to a thermal condition. The influence of *short-term* thermal history on people's thermal sensation, in both Naturally Ventilated (NV) and Air Conditioned (AC) environments, is evaluated in spaces such as transitional spaces in the UK higher educational buildings (Gloria A Vargasa 2014), office buildings in the hot and humid climate of Brazil (Cândido et al. 2010), universities in Pennsylvania, USA, in cold seasons (Fadeyi 2014) and controlled chambers in different climates (Chun et al. 2008, Ken Parsons Lisa Kelly 2010, Nagano et al. 2005, Barrett et al. 2015, Du et al. 2014, Ji et al. 2017, Yu et al. 2013). *Long- term* thermal history and its impact on thermal sensation is also assessed in residential buildings in north and south China by Luo et al. 2016a. It is concluded in these studies that people's thermal sensation and comfort level not only depends on the thermal condition of their current environment, but also previous thermal experiences have a significant influence on their thermal comfort votes.

Adaptive behaviour and control possibilities in an environment can also play important roles on people's thermal perception. Occupants with higher level of control within a space tend to feel more thermally comfortable than their counterparts with lower level or no control in the same environment. Evaluating the occupants' sources of dissatisfaction in the office buildings in winter months in the USA, Finland and Canada reveal that the most frequent problems with employees' thermal comfort is due to lack of control over the space such as no access to thermostat, heater, and operable windows (Huizenga et al. 2006). The improvement of the occupants' thermal comfort (Huizenga et al. 2006, Langevin et al. 2012) and thermal acceptability (Brager et al. 2004, Bauman et al. 1998, Zagreus et al. 2004, Langevin et al. 2012) in NV/ AC office buildings in warm climate, with almost 1.5 °C increase in acceptable temperature range (Brager et al. 2004), clearly shows the significant influence of control possibility on people's thermal comfort within a space. From psychological point of view, occupants who are aware of their control in an environment feel less irritable by uncomfortable thermal conditions (Liu et al. 2014).

According to the mentioned influential factors on people's thermal sensation, providing thermal comfort in the multicultural spaces such as higher learning environments tends to be quite challenging, due to the occupants' various physiological and psychological backgrounds.

Thermal quality of learning environments influences occupants' physical, mental and psychological health; which can affect the teaching and learning performance within the space (Mendell and Heath, 2005, Zomorodian et.al, 2016, Hassanian and Iftikhar, 2015, Schiavon and Zecchin, 2008) and as a result affects the outcome of the education system in each level. Developing the outcome of educational system is an important issue in the UK higher learning environments to attract the international students for studying in this country (Ursula, 2014). Considering the mentioned factors along with the UK commitment to reduce its energy consumption and greenhouse gas emission by 2050 (Committee on Climate Change, 2016, Committee on Climate Change, 2017), attracts more attention to provide thermally comfortable and energy efficient higher educational buildings in this country.

The currently existing environmental guidelines, such as CIBSE-A and EN 15251, introduce the same environmental standards in the UK educational buildings in all levels. In other words, similar thermal requirements are considered for students in all educational stages, from school level to higher learning environments. However, these environmental guidelines cannot be applied in higher learning environments the same as other educational buildings such as primary, secondary and high schools due to the following reasons;

- *Occupants' age and gender:* aging causes increasing the people's comfort temperature (Indraganti and K.D. Rao, 2010, Cena and R. de Dear, 2001, Hwang and C.P. Chen, 2010) and lowering their thermal sensation vote for almost 0.5 scale units (on the 7-point ASHRAE scale) for elderly people (Schellen et.al, 2010). Regarding gender, females tend to have higher neutral temperature (Cena and de Dear, 2001, Morgan, 2003, Karjalainen, 2007). As students in higher educational buildings are in different ages and both genders, they may have various thermal requirements to feel comfortable in an environment.

- *Cultural and background diversity:* personal characteristics (thermal history, culture and social factors) can play an important role on people's thermal sensation in a space (Knez and S. Thorsson, 2006, Kenawy, 2013, Luo et. al. 2016). Therefore, students in the UK higher learning environments, who are from different cultures and nationalities with different thermal experiences and backgrounds, may have various thermal requirements inside the classrooms.
- *Occupants' freedom to do adaptive behaviour:* students in the university classrooms usually have sufficient freedom to choose the appropriate environmental (e.g. opening or closing windows, using the interior blinds) or personal (e.g. changing position, clothing and having a hot or cold drink) adaptive behaviour (Nicol et.al. 2012). Prediction of the students and lecturers' adaptive behaviour in thermally uncomfortable conditions is another factor which should be taken into account in developing proper environmental guidelines.

Due to these reasons, it is required to introduce new environmental standards for higher educational level based on the building function and the occupants' type. Thermal comfort in higher learning environments is evaluated in different climates by considering students' thermal sensation and preferences votes. For instance, the acceptable temperature range and adaptive behaviour for students in university buildings are evaluated in China by Zhang et.al. 2007 and Yao and Lio, 2010; Buratti, 2006 examined the students' comfort temperature in Italy; Hwang, 2006 studied the acceptable temperature range for pupils' in Taiwan, based on the impact of thermal adaptation and adaptive behaviour. In the UK, the influence of thermal history on thermal sensation in transitional lobby spaces, and impact of air quality on occupants' overall comfort is evaluated in Sheffield and Loughborough University (Vargasa, and F.S, 2014, Barbhuiya, 2013). However, none of these investigations considered the influence of personal and environmental factors on students' thermal comfort inside the classrooms in this country. Therefore, a revision and modification on the existing comfort criteria based on the personal factors are essential to create the thermally comfortable and satisfactory environmental condition in higher educational buildings.

The current survey is part of a research project assessing the students' thermal comfort in the UK higher learning environments based on the influential environmental, physiological and psychological human characteristics. In this paper the influence of the students' thermal long and short-term history on thermal comfort perception in Coventry University, UK is evaluated.

2. Methodology

This survey was conducted through a physical evaluation, objective and subjective measurements in three different buildings in Coventry University showing in figure 1.

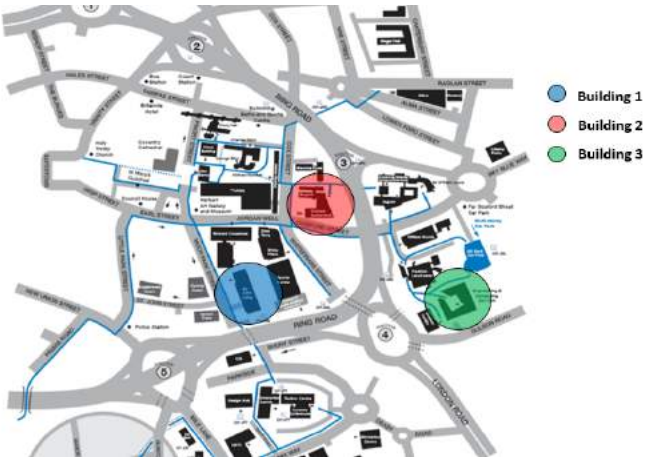


Figure 1. The location of the investigated buildings in Coventry University campus

2.1. Investigated Buildings

The evaluation was conducted in lecture rooms, studios and PC labs in three different buildings at Coventry University in October 2017. Type of the classrooms in each building in which the evaluation was carried out is presented in figure 2. Survey was conducted for 19 times in 6 lecture rooms, where students spend almost 2 or 3 hours with low level of freedom for adaptive behaviour and sedentary activity (1.2 met), 4 PC labs, occupied for 2 or 3 hours tutorial with medium level of freedom, and 3 art studios, where students spend more than 4 hours with high freedom and light activity level (1.6 met) (ISO 7730, 2005). Surveys were conducted in the mornings and afternoon sessions in the free running (FR) modes. Figures 3 to 5 shows a sample of a lecture room, studio and PC lab in buildings 1, 2 and 3 respectively. Also, the description of the investigated buildings 1, 2 and 3 is presented in table 1. Ventilation mode, location of the cooling outlets, windows and door situation, time of the day, sky condition and possible adaptive opportunities were also monitored in each classroom.

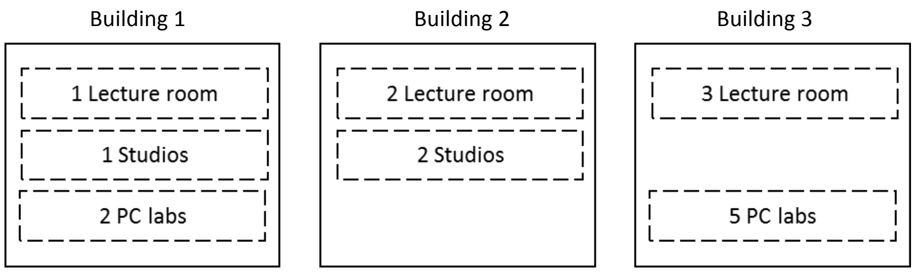


Figure 2. Type and the number of classrooms in each building

Table 1. description of investigated buildings

Building	Construction type	Mode	Number of floors	Investigated floor	Windows
1	Low thermal mass	FR	2	Ground, 1	No window/ operable
2	Heavy thermal mass	FR	4	Ground, 3, 4	Fixed/ operable
3	Medium thermal mass	FR	4	Ground, 1, 2	Fixed/ operable

2.2. Environmental Evaluations

Environmental variables including interior mean radiant temperature, air velocity, relative humidity was recorded during the surveys using SWEMA measurement instrument according to the ISO 7730 with time interval of 5 minutes and accuracy of ±0.1°C, ±0.04 m/s and ±1.6 % respectively. Indoor air temperature, humidity and CO_2 level were also measured using four/ two loggers with accuracy of ± 40 ppm for CO_2 concentration, ± 0.8 ˚c for air temperature and ± 4% for air RH. Loggers placed on approximately 1.1 m above the fixed floor level at the occupants' head height, on a vertical stand, to reflect all subjects' thermal sensation. the CO_2 meters also positioned next to the loggers on a table. Outdoor air temperature was obtained from the nearest meteorological station.

2.3. Questionnaire Survey

To evaluate students' thermal comfort a cross-sectional questionnaire survey was conducted in each classroom. The questionnaire was divided into four main sections including individual questions (such as age, gender, nationality and worn clothes), thermal history and experiences (i.e. climate condition of hometown, thermal condition of family home and current accommodation), thermal comfort votes, (i.e. thermal sensation votes (TSV), thermal preferences votes (TPV) and thermal acceptability) and possibility and preferred adaptive behaviour in the classroom. TSVs were assessed based on the American Society of Heating, Refrigerating and Air- Conditioning Engineers rating scale, cold, cool, slightly cool, neutral, slightly warm, warm and hot. A similar trend was applied to evaluate occupants' TPV, much cooler, cooler, and slightly cooler, without change, slightly warmer, warmer and much warmer. Evaluation of students' thermal history and its impact on TSVs was carried out by analysis of their responses to the questions "How do you describe the climate condition of your hometown compared to Coventry's weather?" and "How long have been in the UK?". Questions for clothing were developed based on ISO 7730 guideline (2005). Almost 8% of the students did not provide the responses due to their busy schedule, but overall data form approximately 650 students in both genders aged from under 21 to 40 was evaluated in this survey. The number of approximately 180, 150 and 320 students participated in the survey in studios, PC labs and lecture rooms respectively. Questionnaires were filled out by students in the last 15 minutes of each class, after at least 1-hour seating in the classroom. The main reason for this is to reduce the disturbance of the class activity and minimize influence of unsettled metabolic rate on TSVs as a result of occupants' previous activities (Goto, et.al. 2000, Haddad, et.al. 2014, Montazami, et.al. 2016). The collected data were statistically analysed using the SPSS statistical package. Correlation between TSVs and students' short and long-term thermal history were evaluated based on the achieved p value and corresponding R^2. This helps to find out which of these factors has the greatest impact on the students' thermal perception in learning environments.

Figure 3. Lecture room in building 1

Figure 4. Studio in building 2

Figure 5. PC lab in building 3

3. Results and Discussion

This section presents the analysis of the students' questionnaire responses and recorded environmental variables. The psychological parameters affecting students' thermal sensation inside the classrooms are introduced based on the achieved results from this statistical evaluation. The influence of students' climatic background (long-term thermal history) and impact of their thermal adaption to the UK climate and influence of current accommodation (short-term thermal history) on students' thermal comfort perception inside the classrooms have been evaluated in the following sections.

3.1. Distribution of Indoor and Outdoor Air Temperature

According to figure 6, outdoor air temperature fluctuates in the range of 7 ^{o}C to 14 ^{o}C during running the survey. Data for indoor air condition is divided into three main sections for buildings 1, 2 and 3 in figure 7. Indoor operative temperature during voting changes from 23 to 25^{o}C in building 1, 19 to 26^{o}C in building 2 and 22 to 24^{o}C in building 3. Comparison of the temperature ranges in buildings 1, 2 and 3 shows smaller variation in building 1 compared to building 2 and 3.

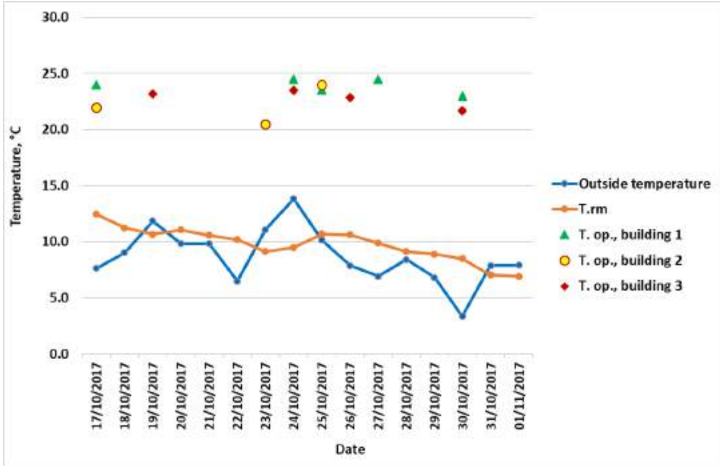


Figure 6. Mean outdoor air temperature (T_{out}) and mean running temperature (T_{rm})

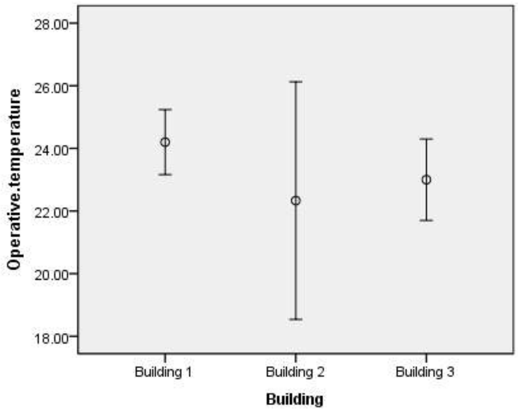


Figure 7. Indoor operative temperature range in building 1,2 and 3

3.2. Distribution of Thermal Sensation Votes

Results for the questionnaire survey show that approximately 153 students in building 1, 201 in building 2 and 294 in building 3 are participated in this survey. In general, 66% of the participants are in the first year, 18% in the second year and 16 % are in the last years of study (table 2).

Table 2. Students' level of study

Students' level	Percentage [%]
1	66
2	18
3 and 4	16

The distribution of TSVs for entire sample in buildings 1, 2 and 3, with average operative temperature of 24 ^{o}C, 22 ^{o}C and 23 ^{o}C respectively. As it can be seen Figure 8-10, Thermal Sensation Vote in Building 1, has a Skew toward the warmer votes while Thermal Sensation vote in Building 2, has a Skew to the colder votes., Thermal Sensation Vote is almost normally distributed compare to the other buildings.

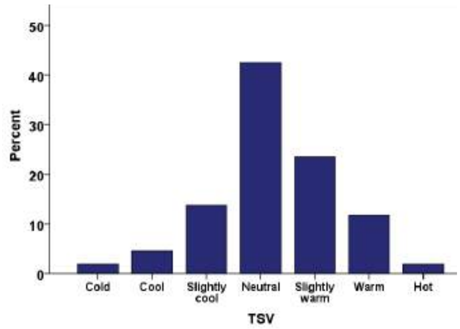


Figure 8. Students' TSV, building 1

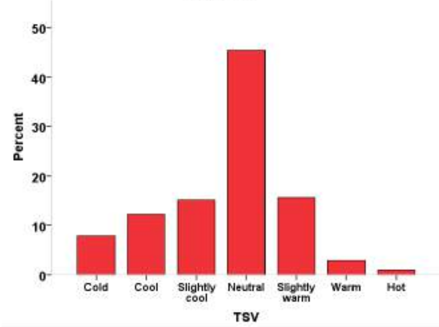


Figure 9. Students' TSV, building 2

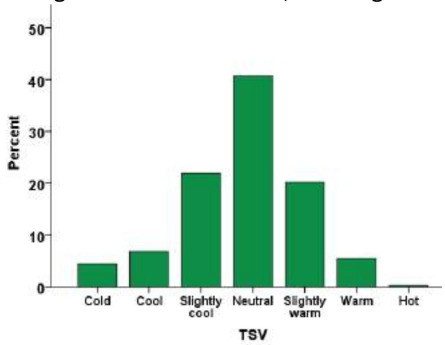


Figure 10. Students' TSV, building 3

3.3. Climatic background and Thermal Sensation Vote

In order to evaluate how climatic background may influence on students' thermal perception, students asked to report if they come from the regions that have similar, warmer and colder compare to the Coventry Climate. The result shows that nearly half of the students are from similar climatic conditions compare to Coventry climate, 35% are from warmer and much warmer and only 16% of them are from colder and much colder climate, figure 11. The result presents a significant correlation between students Thermal Sensation Votes (TSVs) and their climatic background ($p=0.00 <0.05$, $R^2=0.009$). This is a weak correlation; however, the influence of other factors should be investigated.

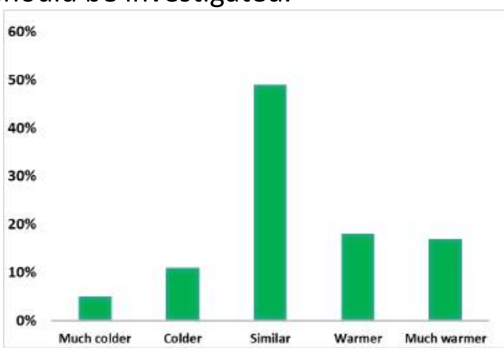


Figure 11. Students' thermal perceptions about their classrooms based on their climatic background

3.4. Students' year of Study and Thermal Sensation Vote

In order to assess the impact of students' thermal adaptation to the UK climate on their thermal comfort in the classroom, thermal sensation votes for the students in the first year, who just moved to Coventry, were compared with students' votes in the higher years. The result shows that there is a significant positive correlation between students' level of study and their Thermal Sensation Vote ($p = 0.00$, $R^2 = 0.02$). According to the influence of thermal history on thermal sensation, there are two main possibilities to justify this correlation; firstly, it is likely that students in higher levels have been in the UK for longer duration and therefore their thermal adaptation to the UK climate influences their Thermal Sensation Votes (TSVs) inside the classrooms. Secondly, it is likely that students in higher years are more familiar with adaptive opportunities exist within their classrooms environment and select an appropriate behaviour to achieve thermal comfort.

3.5. Current Accommodation Thermal Condition and Thermal Sensation Vote

Another major factor which influences the students' TSVs in the classroom is thermal experiences and the level of thermal comfort in their current accommodation which has been measured by analysis of students' responses to the question "How do you describe thermal condition of your current accommodation compared to this classroom?". Table 3, shows the proportion of students votes regarding the thermal condition of their accommodations. The result shows that there is a significant correlation between students' thermal perception at their current accommodation and their thermal sensation votes ($p < 0.05$, $R^2 = 0.1$).

Table 3. Proportion of the students' vote about thermal condition of their accommodations, %

Much colder	5
Colder	24
Similar	38
Warmer	27
Much warmer	7

Considering the correlation significance and the corresponding R^2 for the evaluated factors in table 4, shows the stronger impact on the students' thermal comfort level in their current accommodation compared to the other factors on TSVs. Students' level of the study showing the duration of being in the UK, is another dominant parameter on the occupants' TSVs inside the classrooms. A comparison between these three factors reveals the stronger impact of the students' short-term thermal history than the long-term thermal experiences on their TSVs inside a classroom.

As this evaluation is a small part of a bigger ongoing project, only small part of collected data is evaluated. The other effective parameters on students' TSVs and TPVs will be studied on larger sample size in the next phase of this research project. Also, the state of the correlations between the revealed physical, physiological and psychological factors on students' TSV will be examined in the next steps.

Table 4, Correlation significance and R^2 for influential factors on TSV

Thermal History	Correlated factor to TSV	Sig.	R^2
Long- term	Climatic background	0.00	0.009
Short- term	Level of study	0.00	0.02
	Thermal condition of current accommodation	0.00	0.1

4. Conclusion

Thermal comfort is proven to be a crucial parameter affecting students' performance in learning g environments. This parameter is affected by some environmental and personal factors. This paper aimed to address some influential personal factors such as climatic background, level of study and duration of being in the UK and thermal condition of the accommodations on students' thermal comfort at Coventry University, UK. The result reveals that students' long and short-term thermal history can affect their TSVs inside the classrooms. However, the latter effect seems to be more significant.

5. References

Singh, M. K., Mahapatra, Sadhan, Teller, Jacques (2015) 'Development of thermal comfort models for various climatic zones of North-East India', *Sustainable Cities and Society,* 14, 133-145.

Standard, A. (2004) 'Standard 55-2004', *Thermal environmental conditions for human occupancy*, 9-11.

Katafygiotou, M. C. and Serghides, D. K. (2014) 'Thermal comfort of a typical secondary school building in Cyprus', *Sustainable Cities and Society*.

Nicol, J. F. and Humphreys, M. A. (2002) 'Adaptive thermal comfort and sustainable thermal standards for buildings', 34(563-572).

American Society of Heating, Refrigerating and Air- Conditioning Engineers, ASHRAE standard- 55, 2004, Thermal Environmental Conditions for Human Occupancy

Singh, M. K., Mahapatra, S. and Atreya, S. K. (2011) 'Adaptive thermal comfort model for different climatic zones of North-East India', *Applied Energy,* 88(7), 2420-2428.

Cândido, C., De Dear, R., Lamberts, R. and Bittencourt, L. (2010) 'Cooling exposure in hot humid climates: are occupants 'addicted'?', *Architectural Science Review,* 53(1), 59-64.

Ji, W., Cao, B., Luo, M. and Zhu, Y. (2017) 'Influence of short-term thermal experience on thermal comfort evaluations: A climate chamber experiment', *Building and Environment,* 114, 246-256.

Luo, M., de Dear, R., Ji, W., Bin, C., Lin, B., Ouyang, Q. and Zhu, Y. (2016a) 'The dynamics of thermal comfort expectations: The problem, challenge and impication', *Building and Environment,* 95, 322-329.

Huizenga, C., Abbaszadeh, S., Zagreus, L. and Arens, E. A. (2006) 'Air quality and thermal comfort in office buildings: Results of a large indoor environmental quality survey'.

Langevin, J., Wen, J. and Gurian, P. L. (2012) 'Relating occupant perceived control and thermal comfort: Statistical analysis on the ASHRAE RP-884 database', *HVAC&R Research,* 18(1-2), 179-194.

Brager, G., Paliaga, G. and de Dear, R. (2004) 'Operable windows, personal control and occupant comfort'.

Bauman, F., Carter, T. and Baughman, A. (1998) 'Field study of the impact of a desktop task/ambient conditioning system in office buildings'.

Zagreus, L., Huizenga, C., Arens, E. and Lehrer, D. (2004) 'Listening to the occupants: a Web-based indoor environmental quality survey', *Indoor air,* 14, 65-74.

Liu, J., Yao, R. and McCloy, R. (2014) 'An investigation of thermal comfort adaptation behaviour in office buildings in the UK', *Indoor and Built Environment,* 23(5), 675-691.

Mendell, M.J. and G.A. Heath, Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. 2005: Oxford, UK. p. 27-52.

Zomorodian, Z.S., M. Tahsildoost, and M. Hafezi, Thermal comfort in educational buildings: A review article. Renewable and Sustainable Energy Reviews, 2016. 59: p. 895-906.

Hassanain, M.A. and A. Iftikhar, Framework model for post-occupancy evaluation of school facilities. Structural Survey, 2015. 33(4-5): p. 322-336.

Schiavon, S. and R. Zecchin, Indoor Climate and Productivity in Offices. 2008.

Ursula Kelly, I.M.a.J.W., The Impact of Universities on the UK Economy. 2014, Universities UK: London.

UK climate action following the Paris Agreement. 2016, Committee on Climate Change.

Meeting Carbon Budgets: Closing the policy gap 2017, Committee on Climate Change.

Indraganti, M. and K.D. Rao, Effect of age, gender, economic group and tenure on thermal comfort: A field study in residential buildings in hot and dry climate with seasonal variations. Energy & Buildings, 2010. 42(3): p. 273-281.

Schellen, L., et al., Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady- state condition. 2010: Oxford, UK. p. 273-283.

Cena, K. and R. de Dear, Thermal comfort and behavioural strategies in office buildings located in a hot-arid climate. Journal of Thermal Biology, 2001. 26(4): p. 409-414.
Hwang, R.L. and C.P. Chen, Field study on behaviors and adaptation of elderly people and their thermal comfort requirements in residential environments. Indoor Air, 2010. 20(3): p. 235-245.
Craig Morgan, R.d.D., Weather, clothing and thermal adaptation to indoor climate. CLIMATE RESEARCH, 2003. 24: p. 267–284.
Wang, Z., A field study of the thermal comfort in residential buildings in Harbin. Building and Environment, 2006. 41(8): p. 1034-1039.
Knez, I. and S. Thorsson, Influences of culture and environmental attitude on thermal, emotional and perceptual evaluations of a public square. International Journal of Biometeorology, 2006. 50(5): p. 258-268.
Nicol, F., Adaptive thermal comfort : principles and practice / by Fergus Nicol, Michael Humphreys and Susan Roaf, ed. S. Roaf and M. Humphreys. 2012, London: London: Routledge.
Zhang, G., et al., Thermal comfort investigation of naturally ventilated classrooms in a subtropical region. Indoor and Built Environment, 2007. 16(2): p. 148-158.
Yao, R., J. Liu, and B. Li, Occupants' adaptive responses and perception of thermal environment in naturally conditioned university classrooms. Applied Energy, 2010. 87(3): p. 1015-1022.
C. Buratti, P.R., Thermal – hygrometry comfort in university classrooms: Experimental results in north and central Italy universities conducted with new methodologies based on the adaptive model. 2006, Taylor & Francis Group: London.
Hwang, R.-L., T.-P. Lin, and N.-J. Kuo, Field experiments on thermal comfort in campus classrooms in Taiwan. Energy & Buildings, 2006. 38(1): p. 53-62.
Gloria A Vargasa, F.S., Thermal memory and transition in lobby spaces. Energy Procedia 2014 62: p. 502 – 511.
Saadia Barbhuiya, S.B., Thermal comfort and energy consumption in a UK educational building Building and Environment, 2013. 68: p. 1-11.
Goto, T., Toftum, J., Dear, R.D. and Fanger, P.O., 2000. Thermal sensation and comfort with transient metabolic rates. Proceedings of indoor air, pp.1038-1043.
Haddad, S., Osmond, P., King, S., & Heidari, S. 2014. Developing assumptions of metabolic rate estimation for primary school children in the calculation of the Fanger PMV model. In Proceedings of the 8th Windsor Conference: Counting the Cost of Comfort in a Changing World.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Thermal comfort study in naturally ventilated lecture room based on questionnaire survey

Marta Laska[1] **and Edyta Dudkiewicz**[1]

[1] Faculty of Environmental Engineering, Wroclaw University of Science and Technology, Poland, marta.laska@pwr.edu.pl

Abstract: The internal building conditions strongly influence our well-being therefore it is crucial to create healthy indoor environment. The literature offers a range of models describing the satisfactory indoor conditions, however due to complex nature of the subject the outcomes from these models may differ significantly from the individual sensations of building occupants.

The paper presents the results of survey on thermal sensation votes among students in naturally ventilated lecture room dedicated for 300 students at Wroclaw University of Science and Technology, Poland. The investigation took place during lecture hours between March and May of 2016 and 2017. The respondents answered the questions about their thermal comfort sensations, expectations and discomfort when attending the lecture. The outcomes of the survey present the level of students satisfaction from the indoor environment and its influence on their comfort and feelings like headaches, eye or throat irritation, dry or itching skin, difficulty in concentration, somnolence and overall fatigue. At the same time thermal comfort variables were measured, namely: indoor temperature, humidity and CO_2 level. The paper presents individual thermal comfort sensations trends among students and discusses discrepancies in individual sensations and expectations in comparison with measured parameters and simplified literature models.

Keywords: thermal comfort, survey, naturally ventilated lecture room, CO_2 concentration

1. Introduction

The study of thermal comfort of students and school children in classrooms and lecture rooms has been the subject of many studies conducted over the past years. In publication (Singh at al., 2018) authors presented the summary list of this kind of studies done over last 50 years. The investigations were carried out for various locations and climatic zones of the world, for different groups of students, various sample sizes and times of surveys, also for different technical solutions of HVAC systems. The outcomes from all surveys described in the literature prove that the subject of thermal comfort and its estimation is a complex issue. Individual thermal sensations may vary significantly depending on the indoor and outdoor parameters and individual factors thus cannot be simply estimated.

The literature presents a number of different approaches from the simplest to most complex ones. The most common standard used to describe thermal comfort ISO 7730 is mainly based on the research of P.O. Fanger. It relates to a human physiology and heat transfer. The authors (Nicol et al., 2013) indicate that there has been growing dissatisfaction with climate-chamber-based heat balance models and has been the necessity to create the method of calculating and designing indoor conditions in naturally ventilated buildings where occupants can control their own comfort conditions. This method is widely known as adaptive thermal comfort and is a background of European Standard EN 15251. It is based on the ability of occupants to adapt to changes to their thermal environment (Mishra and Ramgopal, 2013). The literature indicates that an adaptation is an important factor in assessment of individual thermal sensations and can be considered at three dimensions:

physiological, physiological and cultural (Mishra and Ramgopal, 2013). As one can notice, the subject of thermal comfort, its assessment and defining the building occupant's neutral (comfort) temperature is very difficult and complex task.

The literature (Singh, 2018; Fanger, 1970; Nicol et al., 2012; Enescu, 2017; Dudkiewicz and Jeżowiecki 2009a; Laska, 2009; Dudkiewicz and Jeżowiecki 2009b) indicate that the neutral temperature can be related to various indoor parameters where the most common are: air temperature, operative temperature, air velocity, radiant temperature, ect.; personal factors like metabolism, clothing insulation, sex, age, ect., and can be described by different indices and various models (from simple to the complex ones) as described in (Enescu, 2017; Nicol et al., 2012; Laska, 2017).

The literature also presents the wide range of comfort studies for naturally ventilated classroom and lecture rooms for different locations and climate conditions (Zhang et al., 2007; Kim and de Dear, 2018; Hwang et al., 2006; Teli et al. 2012a, Singh et al., 2018; Teli et al., 2012b; Wong and Khoo, 2003).

The definition of indoor comfort in lecture rooms especially of high occupant density is particularly important as unsatisfactory conditions may have a negative influence on learning and students' performance (Zhang et al, 2007). Also other literature (Cui at al., 2013) indicates that warm discomfort environment has a negative effect on both motivation and performance. Therefore in this paper authors would like to check the relationship between the human satisfaction from indoor environment and motivation and performance in naturally ventilated lecture room.

The main objectives of this paper are: to assess the overall students thermal sensation votes and their motivation to work during the lecture; to find the relationship between TSV, PMV and an operative temperature; to analyze students' complains on conditions in terms of their well-being.

2. Overall data

2.1. Room description and climate data

The investigation was carried out in the one of the lecture rooms at the Wroclaw University of Science and Technology, Poland in two spring periods between March and April of 2016, March and May of 2017. Wroclaw is situated in central Europe therefore the climate is temperate. The external conditions during the research varied between 3°C to 12°C and 61% - 93% of RH in spring period of 2016 and between 6°C and 17°C, and 52% - 88% of RH in spring 2017.

The investigated lecture room (Figure 1) is located in the building constructed in 1955 on the top storey and has a form of an auditorium (Majczyk and Tomaszewicz, 2015; Burak at al., 2014; Bocheński and Piskozub, 2015; Laska and Dudkiewicz, 2017). The space area is about 360m^2 with the diminished height of 7,9m at the front to 5,5m at the back of the room. The sunlight is delivered to the room via faced west double-glazed windows of 22,6m^2 equipped in internal sun blinds and 20 ceiling skylights. The investigated room, dedicated for 300 students, is naturally ventilated and served with a classic radiator-based water central heating system.

Figure 1. Investigated lecture room

2.2. Data collection

In the research both, room parameters and individual sensations were investigated. The following indoor parameters were measured: indoor air temperature (T_a), relative humidity (RH) and CO_2 concentration (CO_2). The data was measured by indoor air quality data logger Rotronic CL11 with the accuracy of ±30 ppm, <2,5%RH (10...90%RH), ±0,3K and measuring range of 0...5000ppm; 0...100%RH; -20...60°C. Additionally air temperature and relative humidity loggers Volcraft DL-141TH were used with the accuracy of 1K (from 0 to 40°C) and ±3% and measuring range of -40...70°C, 0...100%RH. Furthermore the pilot measurements (described in sec. 3.1) were taken using SensoData5500 device especially dedicated for indoor comfort and its indices measurements. The accuracy of main parameters are: for temperatures ±0,1K, relative humidity ±2%, air velocity ±0,02m/s and the measuring range of -40...70°C, 0...100%RH and 0,05…5m/s.

The measurements of the parameters and the questionnaire survey were conducted for 18 lectures during two spring periods of 2016 and 2017. Every lecture lasted 90 minutes. The device was located in the central point of the lecture room on the level of student's desk, away from any occupant's influence.

A total number of students participated in field study was 1111, of which 400 males (36%) and 711 females (64%).

Two personal parameters, namely metabolic rate (students performed sedentary activity) and clothing insulation were estimated in accordance of thermal comfort standard ISO 7730.

At the end of each lecture students were asked to fulfil an anonymous questionnaire form and answer the questions about their individual thermal sensations and expectations regarding room temperature, air velocity (more/less airy) and humidity. This information were compared with physical data and further thermal comfort indices were calculated. The questionnaire encompassed also questions regarding overall feelings of the students, their motivation and willingness to work, and also queries about ailments like headaches, eye or throat irritation, dry or itching skin, difficulty in concentration, drowsiness. The respondents were asked about their sex, age, height and weight. Students were asked to define the type of their clothing, defined in the survey as light (e.g. trousers and t-shirt) of clothing insulation 0,43 clo (calculated following the table C.2 of ISO 7730), moderate (e.g. long sleeves or jumper) 0,61 clo or warm (e.g. warm trousers or jacket) 1,03 clo, when fulfilling the questionnaire form.

Individual thermal sensations are defined in the paper as the respondent's Thermal Sensation Vote (TSV) following (Teli et al., 2012; Nastase et al., 2016) which is based on 7-point thermal sensation scale described in ISO 7730. The extreme values from the scale has been excluded as literature (Fanger 1970, Teli et al., 2012a, Teli et al., 2012b) considered them as dissatisfaction from the thermal environment. Also standard ISO 7730 suggests to calculate PMV index only for the range between -2 and +2.

3. Results

3.1. Indoor conditions

The summary of the indoor, outdoor variables and occupancy level for all 18 test days are given in Table 1. Furthermore mean, maximum, minimum and standard deviation (S.D.) of these parameters are presented.

For most of indoor comfort studies operative temperature (T_o) is considered. As T_o is not empirical value therefore it cannot be measured directly (Nicol J.F. and Humphreys M.A., 2010; Nicol et al, 2012; Enescu, 2017). For low air speeds T_o can be calculated by the equation:

$$T_o=0,5T_a + 0,5T_r$$

where T_a is an air temperature and T_r is a radiant temperature.

Table 1. Summary of outdoor and indoor climate

Test day no.	Occupancy level	Outdoor variables		Indoor variables		
		Temperature [ºC]	RH [%]	Operative Temperature [ºC]	RH [%]	CO_2 concentrations [ppm]
1	24	17	52	23,5	35,1	819
2	26	10	87	19,8	44,3	786
3	42	7	79	21,3	34,0	742
4	56	8	67	21,1	36,8	779
5	54	11	88	22,3	38,9	791
6	43	7	57	21,1	27,9	759
7	69	6	81	20,8	35,4	916
8	89	8	60	20,5	30,4	1090
9	44	11	68	22,6	36,1	826
10	55	12	61	22,7	39,7	782
11	58	6	84	22,7	38,0	1075
12	113	10	81	23,3	38,5	1075
13	52	4	87	20,8	35,4	916
14	67	6	73	22,0	31,2	983
15	75	6	73	22,9	32,3	1460
16	77	3	75	21,5	31,3	934
17	71	4	81	20,5	36,4	866
18	92	3	93	21,3	32,9	875
Mean	61,5	7,7	74,8	21,7	35,2	915
Min	24	3	52	19,8	27,9	742
Max	113	17	93	23,5	44,3	1460
S.D.	22,19	3,61	11,83	1,07	3,93	176,16

The research described in this paper meant to be related to T_o parameter. Unfortunately the available equipment used for the survey did not give the possibility to measure radiant temperature that is necessary to calculate T_o, therefore the authors decided to estimate this parameter on the basis of a short pilot test with utilization of SensoData5500. The pilot stage indicated that the discrepancy between mean air and operative temperatures is not significant and reaches only 0,1K thus can be omitted especially that the accuracy of the measuring equipment should aim for ±0,5K for general temperature measurements and ±0,2K for globe and air temperature measurements (Nicol et al., 2012). For the case described in this paper both parameters: the air temperature (T_a) and operative temperature (T_o) are used synonymously.

The interior relative humidity fell within the range of 27,9 to 44,3% during all test days. Mean carbon dioxide level from all measurements equaled 915 ppm. The highest level of CO_2 concentration of 1460 ppm was recorded on 18th of March 2016. At this day after 90 minutes lecture this parameter increased about 823 ppm. At the same time almost 30% of respondents claimed somnolence. The CO_2 level is a good indicator regarding ventilation rate in the room. Its high level, especially when only ¼ of space was occupied as on 18th of March 2016, means that the space was not properly ventilated by opening widows.

During all test days the mean velocity was on a quite low level and came to 0,11m/s.

The occupancy profile during the research varied significantly between 44 and 113 students in 2016, and 24 and 89 students in 2017.

3.2. Clothing insulation

The external temperatures during the investigation varied between 3 to 17°C, therefore an outerwear was often required. For duration of the lecture it was left in a cloakroom. Therefore during the investigation the range of mean clothing insulation value (clo) was narrow - between 0,46 and 0,61 clo.

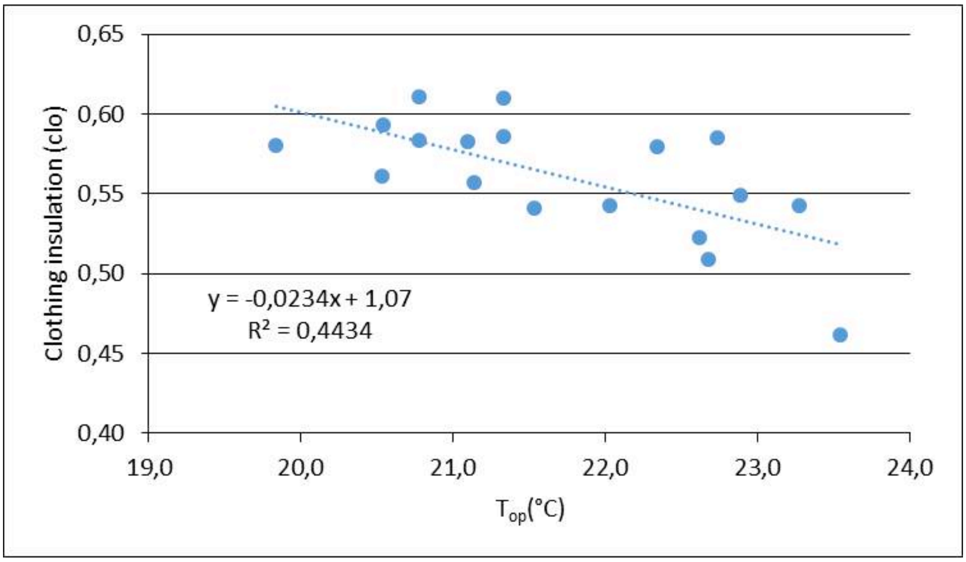


Figure 2. The relationship between occupants' clothing insulation and the room operative temperature

To check the relationship between clo and an operative temperature the linear regression between these parameters was applied. The calculated coefficient of determination amounted to R^2=0,4434 which is not high value, however the expected relationship between these two indices was spotted out - with the increase of operating temperature the clothing insulation decreases. The outcome from the survey and measurements is presented in the Figure 2. Each dot point represents the mean value of the clothing insulation (clo) calculated for every of 18 test days.

3.3. Occupants' responses

During the survey students were asked to define their thermal sensation votes (TSV). The summary of their responses is presented in the Figure 3 below. 44% of respondents defined their individual thermal sensations as neutral, about 47% as slightly warm/cool and the rest of them, namely 9% indicated +/-2. As described in sec. 2.2 the external values of +/-3 were omitted.

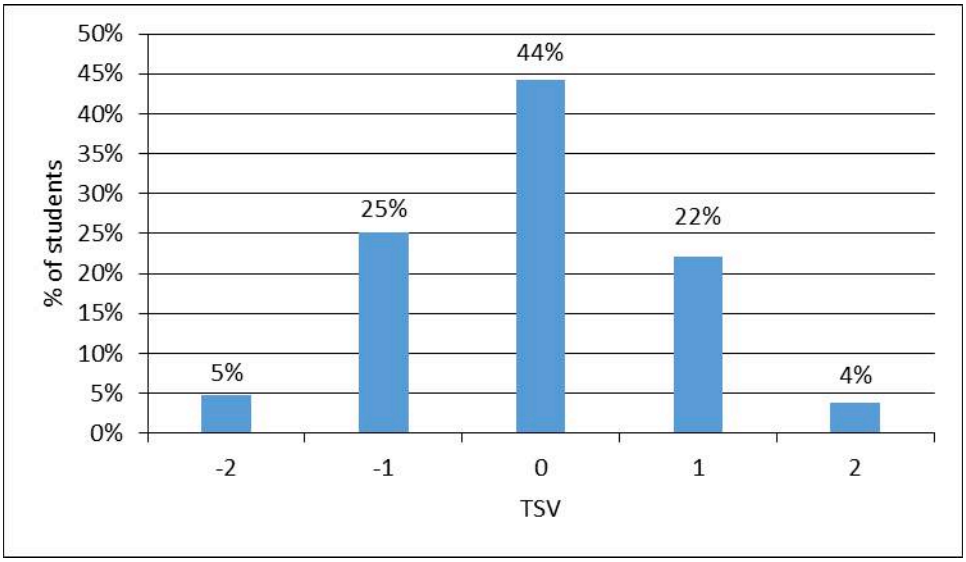


Figure 3. Students' individual thermal sensation votes (TSV)

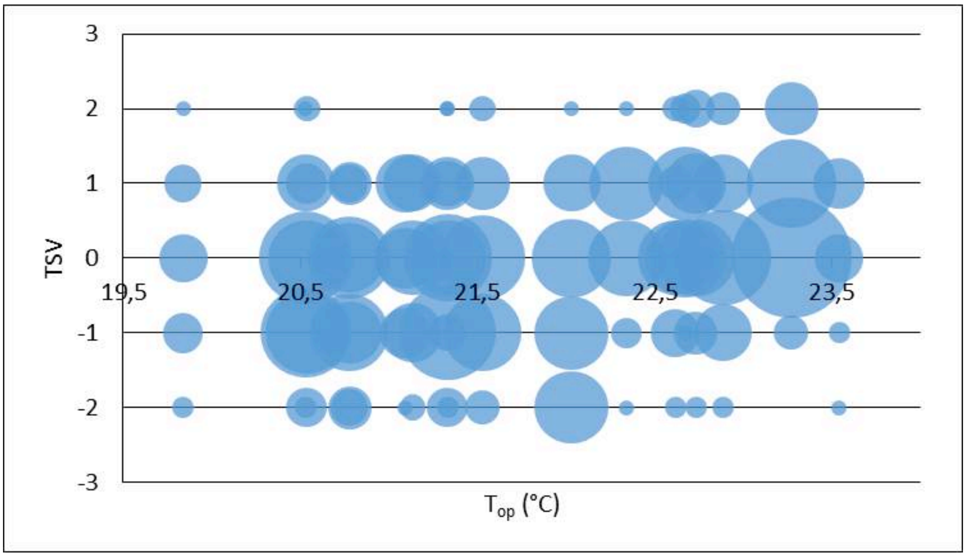


Figure 4. Thermal sensation votes (TSV) per survey against the operative temperature

The relationship between TSV and the room operative temperature is presented in the Figure 4 - the bubble chart. The size of each bubble indicates the number of responses associated to corresponding TSV for every 18 test days. The size of each bubble is proportional to the number of responses, for instance for the 12th test day, when operative temperature was 23,3°C, the biggest group (the biggest bubble) of respondents (62 people) declared TSV=0; during the 1st day, when the indoor temperature was 23,5°C, one person declared TSV=-2, i.e. cool conditions. Some of the bubbles are overlapping due to similar operative temperatures. The Figure 4 indicates that most of the responses were found to be in the comfort bound of ±1 thermal sensation vote.

4. Analysis and discussion

One of the most popular methods for evaluating the neutral temperature is linear regression of thermal sensation votes (TSV) and indoor air temperature (T_a) or operative temperature (T_o). The European Standard ISO 7730 based on Fanger's theory defines neutral conditions for Predicted Mean Vote (PMV) equals 0, however the human body has an ability to adaptation taking place on three levels (Mishra and Ramgopal, 2013) and thus, following the authors (Nastase et al., 2016; Zhang, 2007), the PMV calculated from measurements differs from TSV. In consequence the neutral temperature may vary depending on the external climate conditions and location were the research is taking place. This neutral temperature can be obtained, following (Singh et al., 2018), using regression method and setting the thermal sensation value at 0, that corresponds to "neutral" sensation.

The linear regression equation for the investigated and described in this paper study of naturally ventilated lecture room is defined by the equation:

$$TSV=0{,}2275T_o-4{,}9779$$

The relationship between an operative temperature and mean TSV is presented in the Figure 5. Each dot point represents the mean value of TSV calculated for every test day. For the relationship between TSV and T_o the strength of the correlation was calculated. The Pearson's coefficient of r=0,752 means strong correlation and indicates that the mean thermal sensation of the students (TSV_{mean}) calculated for every test is affected by the room temperature variations. The regression equation is also satisfactory as describes the measurements in almost 60%, with R^2=0,565 (Figure 5).

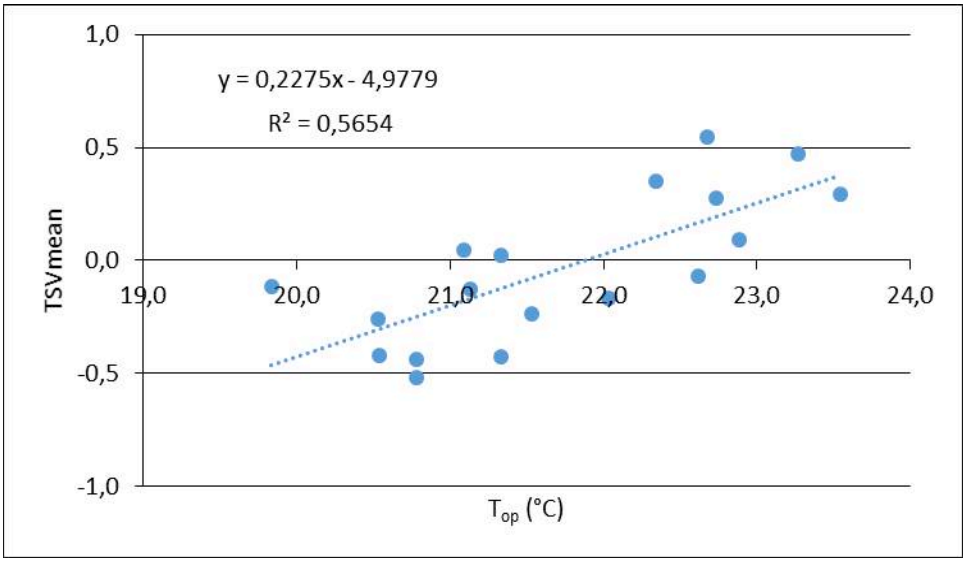


Figure 5. The relationship between mean thermal sensation vote (TSV_{mean}) and the operative temperature

The table 2 presents the regression formulas with their determination coefficients and operative temperatures for TSV = 0 for selected studies found in the literature. On this basis the mean T_o was calculated to be 22,56°C. The calculated operative temperature for the described in this paper investigation equals 21,88°C and is lower from the mean value of about 0,68K. The authors (Zhang et al., 2007), were analyzing a number of publications and spotted out an important fact linked with the human's adaptability to the thermal environment, i.e. the thermal neutral temperatures are very close to the indoor air temperatures. In publications (Hwang et al., 2006) and (Zhang et al., 2007) authors found that in naturally ventilated classrooms, for the average indoor operative temperature of 26°C the neutral operative temperature was 26,2°C. Whereas in naturally ventilated classrooms in a secondary school in Singapore the neutral operative temperature was 28,8°C, when the average dry globe temperature was 30°C (Wong and Khoo, 2003). In naturally ventilated classrooms in a subtropical region the neutral operative temperature was 21,5°C, while the average indoor air temperature was 20,9°C (Zhang, 2007). In the study described in this paper the average indoor temperature was 21,7°C and it corresponds to the calculated neutral operative temperature which equals 21,88°C.

Table 2. Regression formulas of previous studies and the authors.

Author	Regression	T_o for TSV=0 [ºC]	R^2
de Dear Auliciems, 1985	**$TSV=0{,}522T_o-12{,}67$**	**24,27**	**0,9849**
Donnini et al, 1997	**$TSV=0{,}493T_o-11{,}69$**	**23,71**	**0,989**
Cena and de Dear, 1999	**$TSV=0{,}21T_o-4{,}28$ (winter)** **$TSV=0{,}27T_o-6{,}29$ (summer)**	**20,38** **23,30**	**0,8426** **0,888**
Wang et al, 2003	**$TSV=0{,}199T_o-4{,}158$ (male)** **$TSV=0{,}243T_o-5{,}33$ (female)**	**20,89** **21,93**	**0,6582** **0,8002**
Kim and de Dear, 2018	**$TSV = 0.16\ T_{diff} + 0.24$ (Primary school)** **$TSV = 0.15\ T_{diff} + 0.12$ (Secondary school)**	**$T_o = T_n - 1{,}5$** **$T_o = T_n - 0{,}8$**	**0,79** **0,74**
Singh et al 2018	**$TSV = 0.19T_a - 5.04$**	**26,53**	**0,61**
Zhang et al, 2007	**$TSV=0{,}0448T_o-0{,}9628$**	**21,49**	**0,3743**
Teli et al, 2012a	**$TSV=0{,}27T_o-5{,}55$**	**20,56**	**0,545**
Laska and Dudkiewicz	**$TSV=0{,}2275T_o-4{,}9779$**	**21,88**	**0,5654**
		Mean T_o = 22,56	

PMV values for the students were obtained using Fanger's thermal comfort model and according to ISO 7730. Indoor values i.e. air temperature, air velocity and relative humidity were used for data input. Mean clothing insulation values (clo) were obtained from the questionnaires (calculated according to ISO 7730) and fell between 0,46 to 0,61. The students' metabolic rate (met) was estimated considering studying as a light activity therefore, according to ISO 7730, the value of 1,21 was assumed. The linear regression model describing the relationship between PMV and operative temperature is presented in the Figure 6 in orange colour. Along with PMV the Thermal Sensation Votes (TSV) are plotted in the same Figure 6 in blue. Each dot point represents the mean value of TSV calculated for every test day and PMV calculated from average values of measured parameters for each test day. PMV averages are generally lower and out of range of TSV averages defined by the students. The regression analysis of mean PMV gives a thermal neutral operative temperature of 25,5°C. It is nearly 3,6°C higher than the result obtained from regression equation for mean TSV, where T_o was calculated as 21,88°C. The r values are 0,752 for TSV and 0,957 for PMV respectively and indicate strong correlations with T_o in both cases. Additionally high determination coefficient R^2=0,916 indicates strong influence of room temperature on PMV. The discrepancy between TSV and PMV corresponds also with other studies undertaken in UK (Teli et al., 2012a) and in China (Zhang et al., 2007).

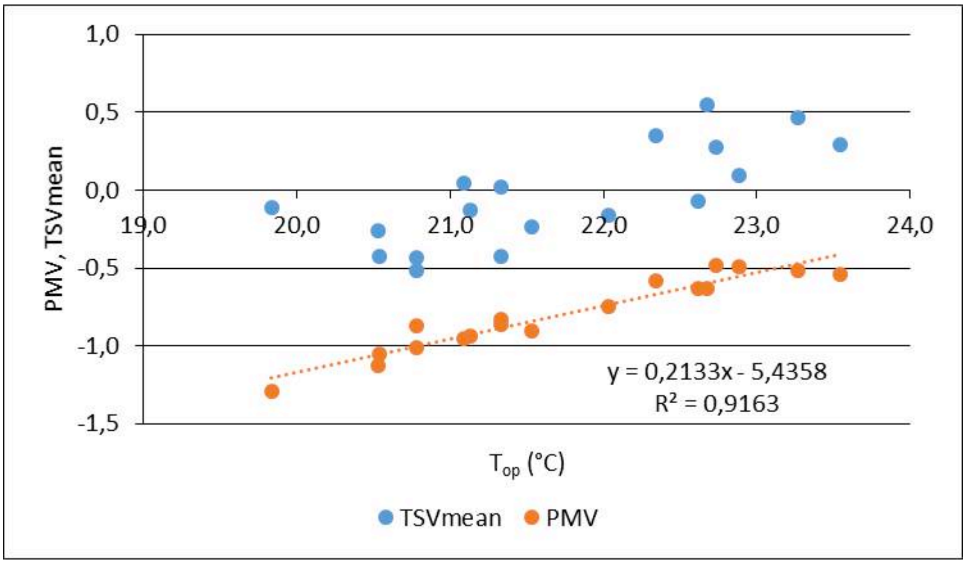


Figure 6. Relationship between mean TSV, predicted mean vote (PMV) and operative temperature

The literature (Cui at al., 2013) indicates that warm discomfort environment has a negative effect on both motivation and performance. Therefore in this paper authors would like to check the relationship between the human thermal comfort and motivation in naturally ventilated lecture room. The students answered the question about motivation to work filling out the questionnaire. There were possible answers: 7 - definitely willing, 6 - very willing, 5 - quite willing, 4 - neither one nor the other, 3 - quite reluctant, 2 - very reluctant, 1 - definitely reluctant. In majority surveys, the most common answer was 5 (Figure 7). At one day 39% of respondents chosen the answer number 4. What is interesting there was one test where the same percentage – 30% of students felt at the same time quite willing (5) and quite reluctant (3) to work. The average evaluation of motivation for each test day was calculated and the rating was between 4,13 and 4,65. Each dot point in the Figure 7 represents the mean percentage of students who declared their motivation grade in the 7-point scale for all days. The vertical black lines indicate the range of this variable from minimum to maximum value. These points and lines were calculated from the total number of questionnaires. An attempt was made to find the influence of the operative temperature on the level of motivation to work. The Figure 8 shows the distribution of average motivation ratings depending on the operative temperature. Each dot point represents the mean value of motivation grade calculated for every test day. A very low determination coefficient and r=0,09 indicate no relationship between the operative temperature and motivation to work. The lack of such dependence is also reflected in large discrepancies between the average thermal sensation votes (TSV) and the average assessment of motivation, as presented in Figure 9, where each dot point represents the mean value of motivation grade calculated for every test day. Summarizing, the thermal sensations resulting from the operative temperature did not translate into motivation to work.

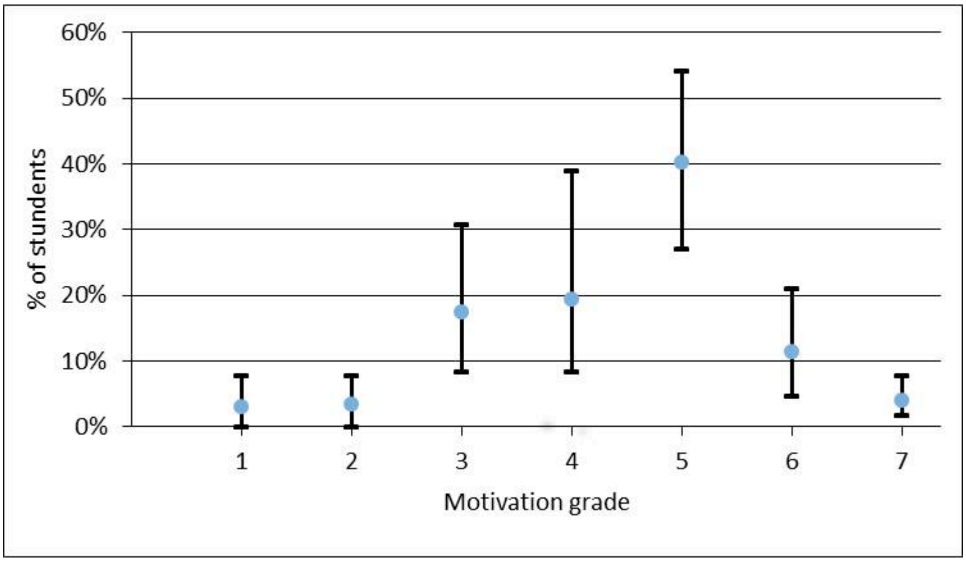


Figure 7. The range and the average motivation grade declared by the students

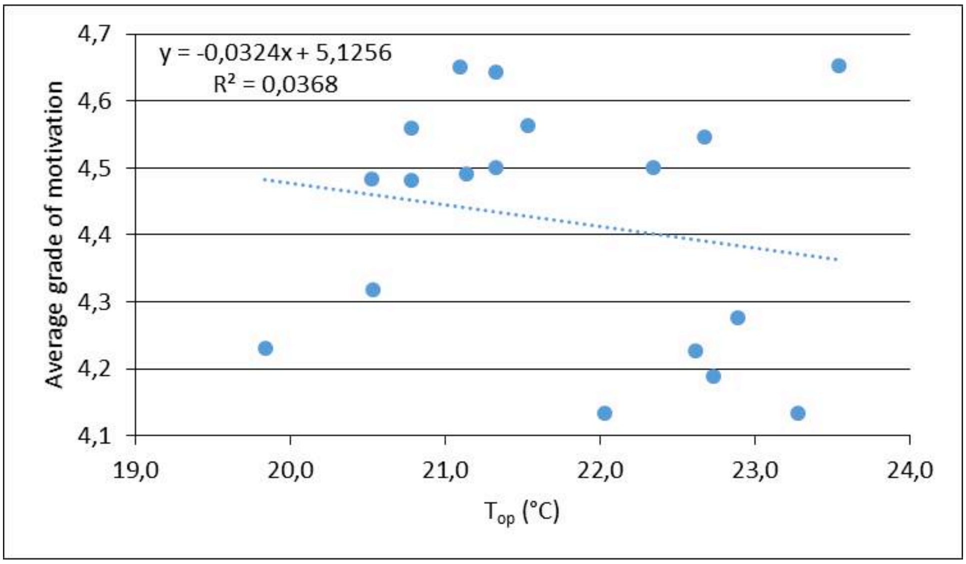


Figure 8. Relationship between the average grade of motivation and the operative temperature

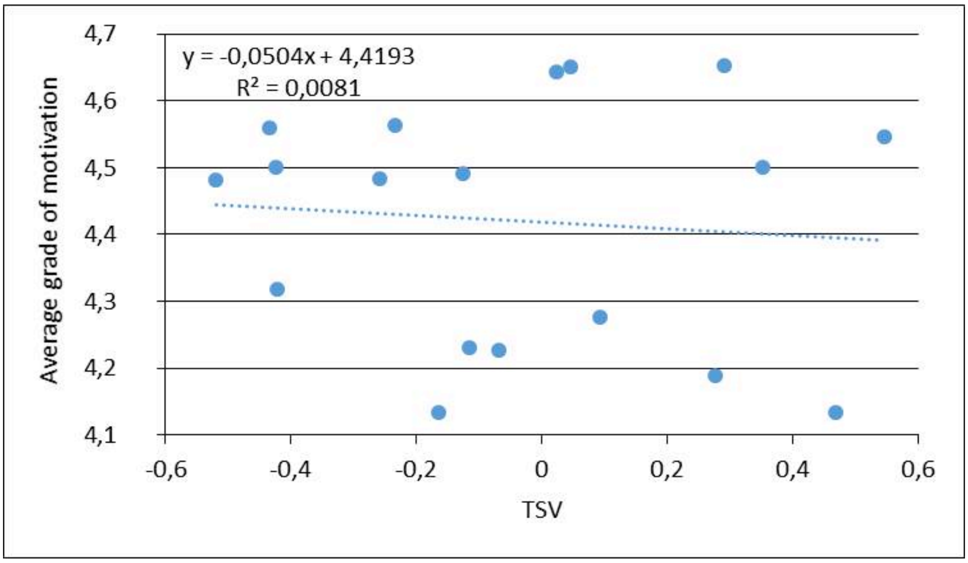


Figure 9. Relationship between the grade of motivation and the thermal sensation votes (TSV)

Aiming to increase the effects and quality of education, an attempt was made to assess the impact of other factors on students' motivation to work. The literature (Griffiths and Eftekhari, 2008) indicates that CO_2 is an important factor influencing the performance of learning ability and concentration. The acceptable CO_2 level for rooms is 1400 ppm (1000 ppm above the external contamination) (Krawczyk et al., 2016) or 1500 ppm as defined by WHO. The results of measurements and calculations of carbon dioxide level in auditorium considered in this article were presented by authors in the article (Laska and Dudkiewicz, 2017). The dependence of the assessment of motivation on CO_2 concentration in the auditorium is shown in the Figure 10. Each dot point represents the mean value of motivation grade calculated for every test day. As presented in the figure, the average motivation rating is higher for lower CO_2 concentrations, but the Pearson's correlation coefficient reaches the value of r=-0,48 and together with R^2 = 0,235 does not satisfy the authors.

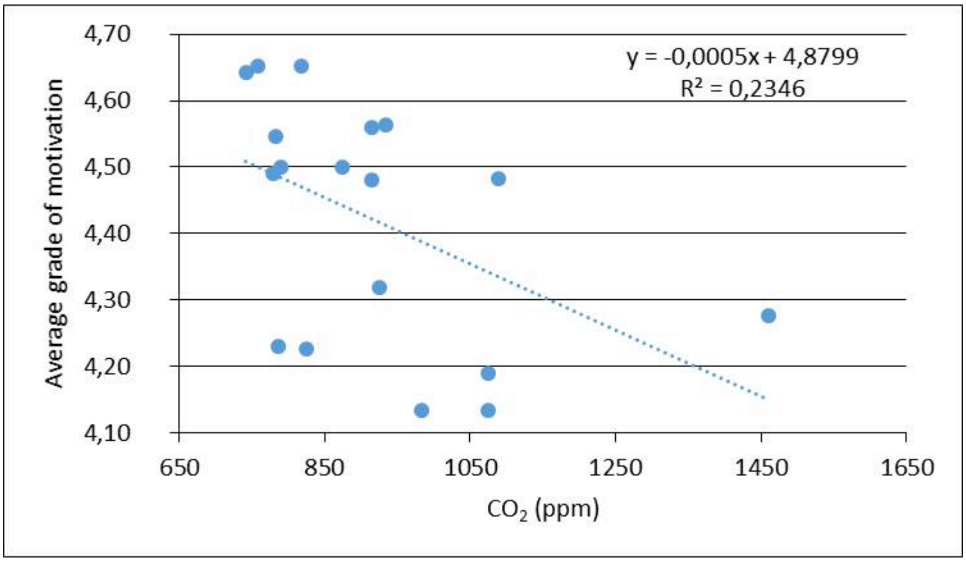


Figure 10. Relationship between the grade of motivation and the CO_2 concentration

In the questionnaires students were asked about other observations perceived during the lectures such as: headache, dizziness, drowsiness, dried/irritated eyes, dried/irritated nose, problems with visual acuity, problems with concentration, dried/irritated skin, general fatigue. The Figure 11 shows the percentage distribution of students' perceptions and feelings, compiled for all the whole survey. The answer "yes" is marked in blue, and was chosen when discomfort occurred; "no" - in orange, when students did not report any aliments; the answer was marked in gray if the student did not give any answer. Most respondents, as many as 40%, complained about drowsiness and 38% on general fatigue; 25% confirmed the problems with concentration and 24% with visual acuity. However, it should be noted that most students, as many as 61% complained of drowsiness on the day when the temperature in the room was 20,5°C even though the average value of motivation was 4,48.

The largest amount of responses (40%) indicating drowsiness led to the study of the impact of somnolence on the average assessment of motivation. The Figure 12 presents the relationship between these parameters. Each dot point represents the mean value of motivation grade calculated for every test day. However comparison of the average of the ratings of the study with the percentage of people experiencing drowsiness for a given test day did not show any correlation. All votes are in the range of 4 and 5. The highest grades of motivation for work (closer to 5) were obtained when 30-40% of people indicated drowsiness, but when fewer people felt drowsy, the motivation assessment was below 4,3.

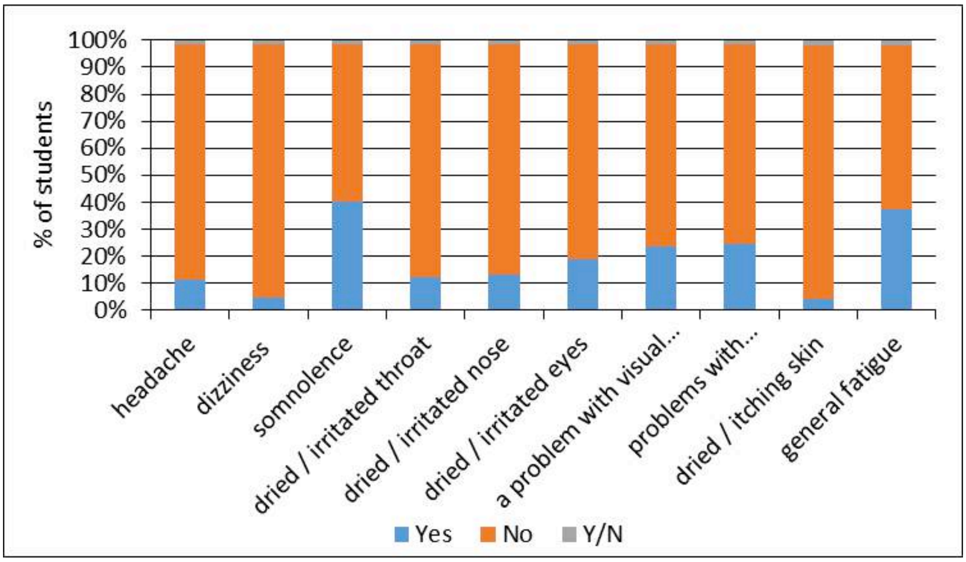


Figure 11. The percentage distribution of students' perceptions and feelings

The difficulty in finding the dependence of motivation to work on various factors indicate the need for further research and surveys. The literature proposes additional questions related to the adaptive strategy, e.g. "What could you do to feel more comfortable?" (Kim and de Dear, 2018). Following this path the authors in further research will expand the survey for additional questions. One of them will be "What could you do to feel higher motivation to work?". This issue will be discussed in an another paper.

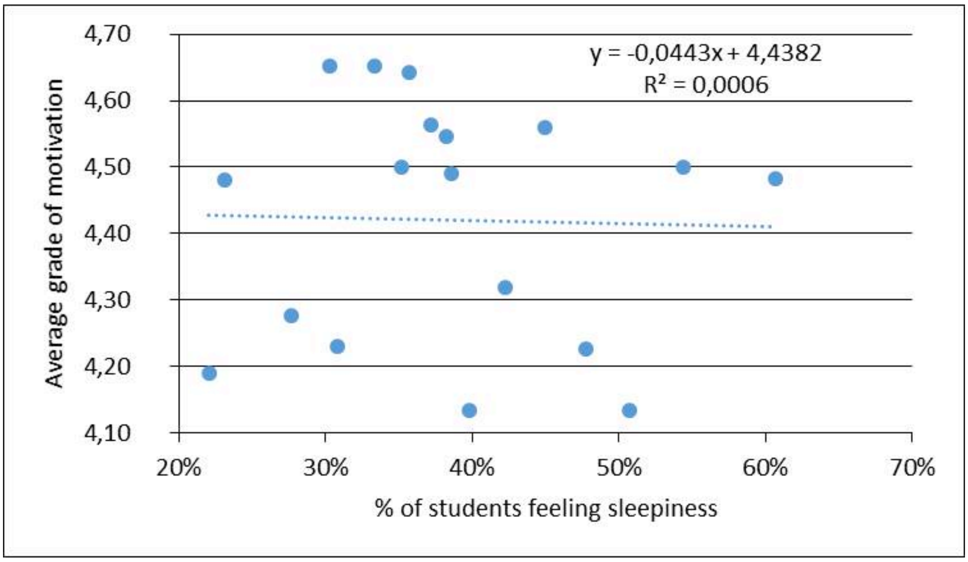


Figure 12. Relationship between the grade of motivation and the drowsiness

5. Conclusion

The research on thermal comfort described in this paper was carried out in auditorium of Wroclaw University of Science and Technology (Poland) during the 18 lectures for students in age of 20-22 years. The length of each lecture was 90 minutes. The questionnaire surveys and measurements were conducted during two spring semesters of 2016 and 2017.

The present study indicates that the range of measured indoor temperatures (where minimum was 19,7°C and maximum was 24,4°C) is perceived by the room occupants as fully acceptable from individual thermal sensations point of view. About 91% of responses were found to be in a comfort band (±1 thermal sensations). The neutral operative temperature for TSV = 0, estimated by the regression equation, was 21,88°C.

The results of the analyzes showed a significant discrepancy between the values of TSV and PMV relative to the operative temperature. The regression analysis of mean PMV gives the thermal neutral temperature of 25,5°C (T_o), nearly 3,6°C higher than the regression result for mean TSV.

The average assessment of motivation to work in all surveys was defined by the majority as 5 - quite willing. At one test, number 4 (neither willing nor reluctant) was chosen by the biggest group of respondents (39%). The operative temperature at this day was 22,7°C. There was also one test were the same percentage – 30% of students felt at the same time quite willing (5) and quite reluctant (3) to work, but at the same time the majority of students were very willing to work (vote ≥ 5) and, what is interesting, in the ambient temperature of 19,8°C.

No relationship was observed between operative temperature, average thermal sensation votes (TSV) and average assessment of motivation. However, the majority of higher motivation ratings were in the temperature range of 20,5 – 21,5°C.

The dependence of the assessment of motivation on CO_2 concentration in the auditorium is not clear. The average motivation rating is higher for lower CO_2 concentrations, but the Pearson's correlation coefficient reaches r=-0,48 and together with R^2 = 0,235 is not satisfactory.

In the questionnaires students were asked about other observations perceived during the lectures such as: headache, dizziness, drowsiness, dried/irritated eyes, dried/irritated nose, problems with visual acuity, problems with concentration, dried/irritated skin, general fatigue. The most common ailment was somnolence and general fatigue. However they did not influenced on the overall work motivation. About 25% of respondents had problems with concentration and visual acuity.

The outcome from the research indicates the need to extend the questionnaire with new questions that will be helpful in finding additional factors influencing students' motivation to work and methods of increasing it.

Acknowledgements

The participation in the conference was co-financed by the Faculty of Environmental Engineering, Wroclaw University of Science and Technology, Poland (No. 0401/0007/17).

6. References

Bocheński S., Piskozub J., 2015. Construction of the Wrocław University of Technology buildings for the Faculty of Electrical Engineering D1 and Faculty of Aviation Engineering D2 – history of some illusion. *Journal of Heritage Conservation*, 4, pp 65-73

Burak M., Dackiewicz K., Pawlikowski J.M., 2014. *Budynki i laboratoria Politechniki Wrocławskiej,* Politechnika Wrocławska, Wrocław, Poland

Cena K., de dear R.J. 1999. Field study of occupant comfort and office thermal environments in a hot, arid climate. *ASHRAE Trans* 105(2) pp 204–217.

de Dear R.J., Auliciems A., 1985. Validation of the predicted mean vote model of thermal comfort in six Australian field studies. *ASHRAE Trans* 91(2B), pp 452–468.

Donnini G., Molina J., Martello C., Lai D.H.C., Lai H.K., Chang C.Y., Laflamme M., Nguyen V.H., Haghighat F., 1997. Field study of occupant comfort and office thermal environments in a cold climate. *ASHRAE Trans*, 103 (part 2), pp 205–220.

Dudkiewicz E., Jeżowiecki J., 2009a Measured radiant thermal fields in industrial spaces served by high intensity infrared heater. *Energy and Buildings*., 41, 1, pp. 27-35.

Dudkiewicz E., Jeżowiecki J., 2009b. Local discomfort on the work station *Annual Set The Environment Protection*. 11, part 2, pp 751-759

EN 15251 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics

Enescu D., 2017. A review of thermal models and indicators for indoor environments. *Renewable and Sustainable Energy Reviews,* 79, pp 1353-1379

Fanger P.O., 1974. *Komfort cieplny*, Arkady.

Griffiths M., Eftekhari M., 2008, Control of CO2 in a naturally ventilated classroom. Energy and Buildings 40, pp 556-560

Hwang R.L., Lin T.P., Kuo N.J. 2006. Field experiments on thermal comfort in campus classrooms in Taiwan. *Energy and Buildings*, 38, pp 53–62.

ISO 7730, Ergonomics of the Thermal Environment - Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, ISO, Geneva, 2005.

Kim J., de Dear R. 2018. Thermal comfort expectations and adaptive behavioural characteristics of primary and secondary school students. *Building and Environment,* 127, pp 13-22

Krawczyk D.A., Rodero A., Gładyszewska-Fiedoruk K., Gajewski A., 2016. CO_2 concentration in naturally ventilated classrooms located indifferent climates—Measurements and simulations *Energy and Buildings* 129, pp 491-498

Laska M. Thermal comfort study of naturally ventilated office. 9th Conference on Interdisciplinary Problems in Environmental Protection and Engineering EKO-DOK 2017 [an electronic document] : Boguszów-Gorce, Poland, April 23-25, 2017 /ed. by B. Kaźmierczak [et al.]. [Les Ulis] : EDP Sciences, 2017. art. 00050, s. 1-8. (E3S Web of Conferences, ISSN 2267-1242; vol. 17)

Laska M., Dudkiewicz E., 2017. Research of CO_2 concentration in naturally ventilated lecture room. *International Conference on Advances in Energy Systems and Environmental Engineering (ASEE17)*, Wrocław, Poland, July 2-5, 2017, EDP Sciences, 2017. art. 00099, s. 1-8. (E3S Web of Conferences, ISSN 2267-1242; vol. 22)

Laska M., Jadwiszczak P., Syposz J., 2009. Thermal comfort - state of art. *Industrialised, integrated, intelligent construction* [an electronic document]: handbook 1 / ed. by Ian Wallis, Lesya Bilan & Mike Smith. [Bracknell, Berkshire], I3CON BSRIA, pp 114-129.

Majczyk J., Tomaszewicz A., 2015. Aleja Profesorów (Avenue of Professors) in the main campus of Wrocław University of Technology – history of the spatial system development, *Architectures* 1(41), pp 69-86

Martinez-Molina A., Boarin P., Tort-Ausina I., Vivancos J.L., 2017. Post-occupancy evaluation of a historic primary school in Spain: Comparing PMV, TSV and PD for teachers' and pupils' thermal comfort. *Building and Environment,* 117, pp 248-259

Mishra A. K., Ramgopal M. 2013. Field studies on human thermal comfort - An overview. *Building and Environment* 64, pp 94-106

Nastase I., Croitoru C., Lungu C. 2016. Questioning of the Thermal Sensation Vote Index Based on Questionnaire Survey for Real Working Environments. *Energy Procedia*, 85, pp. 366-374

Nicol F., Humphreys M., Roaf S., 2012. *Adaptive Thermal Comfort: Principles and Practice,* Routledge

Nicol J.F., Humphreys M.A., 2010. Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251*, Building and Environment* 45 (1) pp 11–17

Singh M. K,. Kumar S., Ooka R, Rijal H. B., Gupta G., Kumar A. 2018 Status of thermal comfort in naturally ventilated classrooms during the summer season in the composite climate of India. *Building and Environment*, 128, pp 287–304

Teli D., Jentsch M. F., James P.A.B., Bahaj A.S. 2012a. Field study on thermal comfort in a UK primary school. *7th Windsor Conference: The changing context of comfort in an unpredictable world Cumberland Lodge*, Windsor, UK, 12-15 April 2012. London: Network for Comfort and Energy Use in Buildings

Teli D., Jentsch M.F., James P.A.B., 2012b. Naturally ventilated classrooms: an assessment of existing comfort models for predicting the thermal sensation and preference of primary school children. *Energy and Buildings,* 53, pp 166-182

Wang Z.J., Wang G., Lian G.W., 2003. A field study of the thermal environment in residential buildings in Harbin. *ASHRAE Trans*; 109(2), pp 350–355.

Wong N.H., Khoo S.S. 2003, Thermal comfort in classrooms in the tropics. *Energy Buildings*, 35, pp 337–351.

Zhang G., Zheng C., Yang W., Zhang Q., Moschandreas D. J., 2007. Thermal Comfort Investigation of Naturally Ventilated Classrooms in a Subtropical Region. *Indoor and Built Environment*, (16)2, pp 148–158

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Thermal comfort in Classrooms: A critical review

Manoj Kumar Singh[1], Ryozo Ooka[2], Hom B Rijal[3]

[1] Department of Human and Social Systems, Institute of Industrial Science, The University of Tokyo, 4-6-1, Komaba, Meguro-ku, Tokyo 153-8505, Japan, email: mksinghtu@gmail.com
[2] Department of Human and Social Systems, Institute of Industrial Science, The University of Tokyo, 4-6-1, Komaba, Meguro-ku, Tokyo 153-8505, Japan, email: ooka@iis.u-tokyo.ac.jp
[3] Faculty of Environmental Studies, Tokyo City University, 3-3-1 Ushikubo-nishi, Tsuzuki-ku, Yokohama, 224-8551, Japan, email: rijal@tcu.ac.jp

Abstract: Classrooms play an important role in every student's life as the quality of thermal environments also influences a student's performance and well-being. It is well known that at each educational stage, curricula demand different learning approaches and types of systematic thinking, requiring increasing levels of concentration. The absence of any standard or reference document relating to the design of appropriate classrooms based on educational stages is worsening the situation. Total 81 research articles selected from the Scopus database were considered for this study. It was found that at each education level in the studied schools, students were highly dissatisfied with the prevailing indoor thermal environments. Primary school students were least sensitive to outdoor temperature changes. There are relatively few published articles published on thermal comfort in classrooms. Based on the reported findings, no consistent temperature change was found necessary to record a shift of one thermal sensation vote by students in classrooms. This study proposed different adaptive comfort equations for use in the estimation of indoor comfort temperature in classrooms at different educational stage. Moreover, the study provides robust evidence that there is a need for a separate set of different guidelines or standards for students of different ages in different stages of their education.

Keywords: Thermal comfort, Adaptive thermal comfort, Classroom, Naturally ventilated, Air-conditioned, Primary school, Secondary school, University classrooms

1 Introduction

1.1 Overview

It is widely recognised that educational systems across the world involve different stages of learning where student spend different amounts of time in the classroom depending on his/her age (de Dear et al, 2015; Djongyang et al, 2010; Lee et al, 2012; Mendell and Heath, 2005; Wargocki and Wyon, 2013; Zomorodian et al, 2016). Students between the ages of two to twenty-six years old spend a considerable amount of their waking hours in a classroom (approximate ages from kindergarten to university) (de Dear et al, 2015; Djongyang et al, 2010; Lee et al, 2012; Mendell and Heath, 2005; Wargocki and Wyon, 2013). In the classroom a student also needs to concentrate to the highest levels as he/she is continuously learning new topics, improving his/her skills and capacity for systematic thinking (Lee et al, 2012; Wargocki and Wyon, 2013; Yang et al, 2013). Educational buildings, and especially classrooms, should have the characteristics that provide a stimulating environment to enhance the learning process (Giuli et al, 2012; Mendell and Heath, 2005; Mishra and Ramgopal, 2015; Turunena et al, 2014). Many studies published since the 1960's suggest a strong correlation between the thermal environments and air quality within classrooms and student's performance and well-being (Auliciems, 1969; de Dear et al, 2013; Djongyang et al, 2010; Hoof, 2008).

More recently the teaching and learning approaches and strategies applied in classrooms is evolving around the increasing role and use of ICT systems at various stages in education systems (Djongyang et al, 2010; Gao et al, 2014; Kruger et al, 2004; Nico et at, 2015; Stazia, 2017; Teli et al 2014). With so many changes at play, it is now important to categorize the indoor environment conditions within classrooms that are resulting from new and emerging approaches to the design of classrooms at the different educational stages(Djongyang et al, 2010; Kruger et al, 2004; Di Perna et al, 2011). Higher up the education stages, the increasing use of computers is resulting in a revolution in the conventional teaching spaces once dominated by teachers standing beside blackboards (Djongyang et al, 2010; Kruger et al, 2004). With the growing dependence of classroom on technology comes increasing energy consumption associated with both the operation and maintenance of buildings (Huang et al, 2015; Nicol and Humphreys, 2002; Yang et al, 2014; Yau, 2014). Absence of standard that deal specifically with indoor thermal environment of education buildings and classrooms for students of different ages in different stages of their education is compelling the designers and architects to use the existing standards such as ASHRAE 55, CEN 15251, ISO-7730 as reference documents (ASHRAE 55, 2013; CEN 15251, 2007; ISO-7730, 2005). A review of the related literature indicates that architects and engineers are treating the design of educational buildings like that of any other public buildings (Djongyang et al, 2010; Stazia, 2017; Martinez-Molina, 2017; Huang and Hwang, 2016; Almeida and de Freitas, 2015). It is well known to the thermal comfort research community that the database of ASHRAE-55, ISO 7730 and CEN 15251 standard mainly contain data collected during comfort studies done on healthy adults in public buildings across the world (ASHRAE 55, 2013; CEN 15251, 2007; ISO-7730, 2005). Several studies done in air-conditioned and free running classrooms concluded that there are high levels of dissatisfaction reported by students towards the prevailing thermal environments of the classrooms (Auliciems, 1969; Auliciems, 1972; Auliciems, 1973; Auliciems, 1975; Humphreys, 1973; Humphreys, 1977; Kwok, 1998; Liang et al, 2012; Puteha et al, 2012; Teli et al, 2012; Wong and Khoo, 2003; Yun et al, 2014). It is very interesting to note that this trend is prevalent not only in the classrooms of developing countries but also in the developed countries (Auliciems, 1969; Auliciems, 1972; Auliciems, 1973; Auliciems, 1975; Humphreys, 1973; Humphreys, 1977; Kwok, 1998; Liang et al, 2012; Wong and Khoo, 2003; Yun et al, 2014). The reason for this is that the reference standards against which the comfort experienced by students are typically gauged were historically formulated for steady state office environment where clothing and activity levels were deemed to be fixed as was the density of occupants in spaces (occupants/m2) (Al-Rashidi, 2012; Auliciems, 1969; Auliciems, 1972; Auliciems, 1973; Auliciems, 1975; Humphreys, 1973; Humphreys, 1977; Kwok, 1998; Liang et al, 2012; Serghides et al, 2015; Wong and Khoo, 2003; Yun et al, 2014).

1.2 Objectives of this study

At each stage of schooling (kindergarten, elementary school, primary school, secondary school, senior secondary school/high school and university) teaching and objectives are set to facilitate the learning by students of certain skill sets (Djongyang et al, 2010; Auliciems, 1969; Auliciems, 1972; Auliciems, 1973; Auliciems, 1975; Humphreys, 1973; Humphreys, 1977; Kwok, 1998; Liang et al, 2012; Wong and Khoo, 2003; Yun et al, 2014). Based on the skill set requirements at each stage of schooling, lessons to boost systematic thinking and the physical activity of students have been devised accordingly (Djongyang et al, 2010;

Auliciems, 1969; Auliciems, 1972; Auliciems, 1973; Auliciems, 1975; Fong et al, 2015; Humphreys, 1973; Humphreys, 1977; Kwok, 1998; Liang et al, 2012; Wong and Khoo, 2003; Yun et al, 2014). In many cases, students are required to adopt uniforms are from the elementary to high school stages. These uniforms are typically specified and designed by adults who do not wear them and have a little working grasp of activity related metabolic rates and experiences (Barrett et al, 2013; Choi et al, 2013; Katafygiotou and Serghides, 2013). There appears to be little or no scientific understanding applied to the selection of uniforms (de Dear et al, 2015; Giuli et al, 2015; Nam et al, 2015) which reflects the clear disconnect between the experiences, requirements and aspirations of students and those of the adults who dictate the dress codes and environments they occupy at school. Despite a number of studies carried out to establish a link between student's performance indoor environment quality (IEQ) and IAQ, there remains a considerable gap in the basic information and understanding necessary to draw correct conclusions on best ways forward in the challenge of designing 'optimally Fit for Purpose' teaching and learning spaces, behaviours and clothing and furnishing infra-structures in the rapidly evolving landscapes of classroom practices (Almeida and de Freitas, 2015; Nam et al, 2015; Serghides et al, 2015).

The more obvious gaps in the information available to good designers include:

a) What is the status of thermal comfort and preferences of students in primary school, secondary school and university classrooms operated under NV/FR and air-conditioned mode?
b) Depending upon climate, do students perform better in air-conditioned or naturally ventilated or mixed mode operated classrooms and if so which ones?
c) How to test the performance of students (should the evaluation be spread over months or weeks)?
d) How to normalize the test procedure to judge the performance of students (because different students may perform better in different tasks depending upon their interest and motivation)?

This paper is divided into different sections based on the different stages of student schooling (primary school, secondary school and university students) and tries to explore the answers to the gaps in the information mentioned above. Data relating to comfort parameters, schooling stage, classroom operation mode (NV/FR, mixed mode and air-conditioned) and sample sizes are extracted from the articles and analyzed to draw conclusions on research trends, thermal comfort and preferences in classrooms operated under NV/FR and air-conditioned mode and regression equations of published articles based on mode of operation of classrooms at each level. Finally, the authors proposed adaptive comfort equations, highlight the gaps in the classroom comfort studies and propose a way forward for the identification of improved and systematic performance-based criteria that include also indicators for the wellbeing of students.

2 Thermal comfort assessment approaches

Most accepted way to define the thermal comfort conditions for a group of subjects (sample size) in field or in laboratory is to carry out subjective evaluation by recording subject's thermal feelings, preferences, physical and personal comfort variables and statistically relate them to arrive at some quantity which will be acceptable to 80% of the sample size (ASHRAE, 2013, ISO, 2005). Thermal comfort studies done over the years suggest that the diversity in climate, geographical location, built environments and subjects have a strong influence on the acceptable thermal comfort conditions for that climate, geographical location and built environment (Auliciems, 1981; Brager and de Dear, 1998; de Dear and Brager, 1998; Fanger, 1970; Humphreys, 1975; Humphreys, 1978; Humphreys and Nicol, 1998; Karjalainen, 2012). This has also encouraged scientists and researchers to carry out thermal comfort research in different parts of the world, covering different climates and built environments applying heat balance approach and adaptive model (Brager and de Dear, 1998; CEN 15251, 2007; Fanger and Toftum, 2002; Feriadi and Wong, 2004; Karjalainen, 2012; Karyono, 2000; McCartney and Nicol, 2002; Mallick, 1996; Nicol and Humphreys, 2002; Nicol, 2004; Wong, 2002; Mishra and Ramgopal, 2013; Teleghani et al, 2013; Yang et al, 2014).

3 Methodology of the study

To carry out this study "Scopus database" is searched with keyword "thermal comfort study in classrooms". Total 81 research articles appeared in the search out of which there is one review article on "educational buildings" (Figure 1). The present study gives detail insights of the thermal comfort studies done in the classrooms in different parts of the world. To analyze the data in detail the research articles are broadly classified into three major categories.

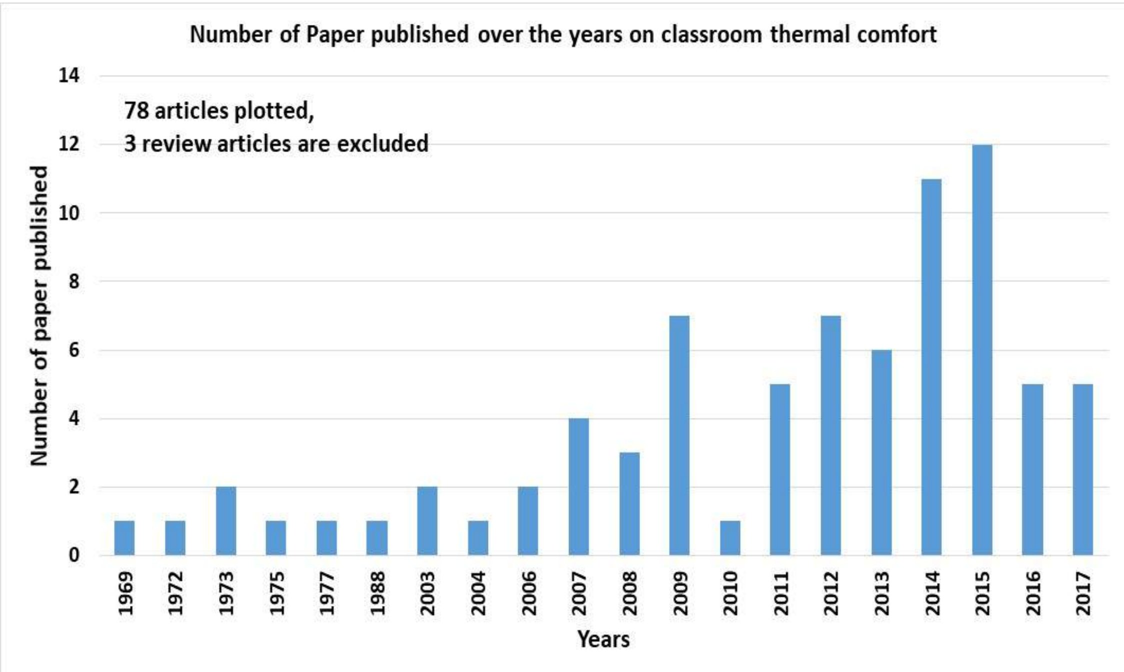


Figure 1 Number of paper published over the years in classroom thermal comfort

a) Kindergarten, elementary and primary school classrooms: Studies done in these classrooms are clubbed together and in this study, it is referred as "primary school classroom" for analysis.
b) Secondary, senior secondary and high school classrooms: Studies done in these classrooms are merged together and referred as "secondary school classroom" for analysis.
c) University classroom

The basis of this classification is present in Table 1. Also if a particular study has considered primary and secondary school classrooms as their study area then the particular research article is counted for both primary and secondary school classroom study. A similar approach is also adopted for the research that had considered secondary and university classrooms as their study area. Table 1 presents the characteristics of the classrooms extracted from 81 research articles, at different educational stages in different parts of the world. From the table, we can see that the functionality and density of the classrooms are quite different at different stages of schooling starting kindergarten. To know the share of classroom thermal comfort studies in overall thermal comfort studies, Scopus database was searched again with a keyword "Thermal comfort". It returned 16504 articles (Figure 2). Detailed analysis of this search and corresponding numbers are done in later sections.

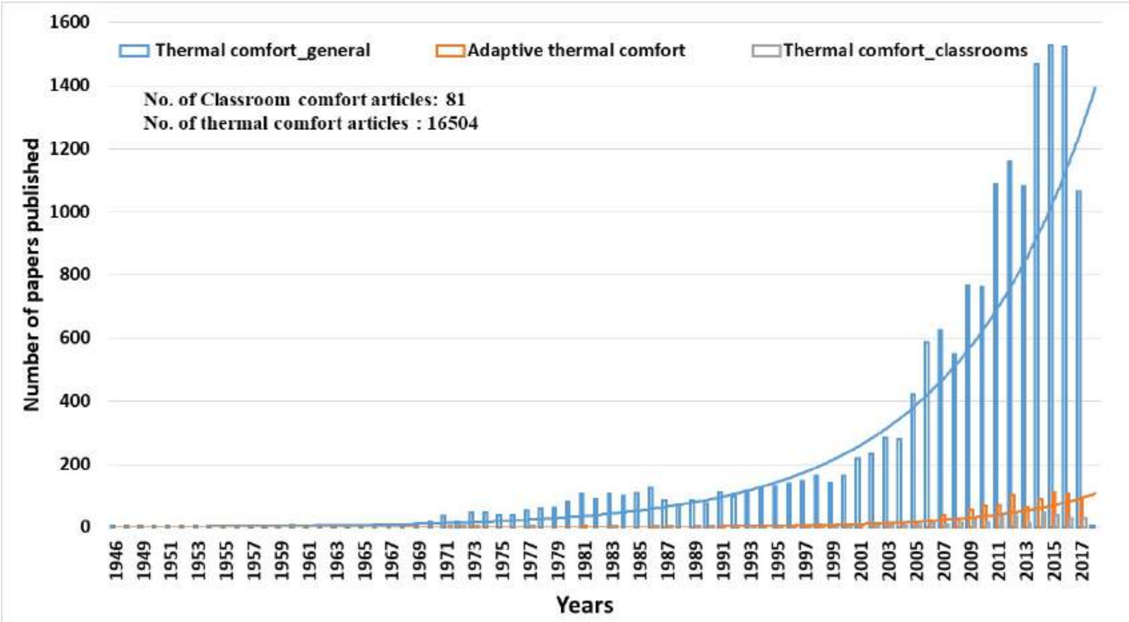


Figure 2 Number of documents on Scopus scientific database when search with keywords "Thermal comfort, Adaptive thermal comfort and thermal comfort in Classroom" (accessed on 11th Sept 2017)

In the context of different educational stages, 81 research articles are again sub-categorized into different operation mode of classrooms. Different operation mode of classrooms are considered with following definitions

i) *Naturally Ventilated (NV):* A Classroom is constructed to operate under free running (FR) condition 12 months a year and same is considered under the study period.

ii) *Free running (FR):* A classroom is constructed primarily to operate the heating system (HS) or cooling system (CS) but during the study period either HS or CS was switched off.

iii) *Heating system (HS):* A classroom is constructed with the heating system and during the study period heating system was switched on.

Table 1 Characteristics of classrooms at different educational stages

Parameters	Classrooms at different educational stages			
	Kindergarten	**Elementary/Primary**	**Secondary/Sr. Secondary**	**University**
Occupants	Children	Children	Children	Adults
Age group (Years approximately)	3-6	7-11	12-18	19-26
Density	Very high	moderately high	high	low
Furniture	Not always	Desk and benches. Each occupied by 1 to 3 students	Desk and benches. Each occupied by 1 to 3 students	Desk and benches. Each occupied by 1 to 2 students
Classroom types	Learning + play	Lecture	Lecture + laboratory	Lecture + laboratory
Duration of Occupancy (hours)	3-8(continuous)	4-6(continuous)	6-7(continuous)	Students visit rooms for lecture and occupy the room of 1 or 2 hours per lecture continuously. So students experience transient thermal environment almost all the time
Layout of class	No specific layout	Lecture rooms/Lecture theatres. Students sit in rows	Lecture rooms/Lecture theatres. Students sit in rows	Lecture rooms/Lecture theatres. Students sit in rows
Indoor environmental control	No Control. As judged by adults for both NV and (CS+ HS)	No Control. As judged by adults for both NV and (CS+ HS)	Partial control. Some controls in NV but no control in (CS+ HS)	Some control in NV and in (CS+ HS)
Lighting	Day lighting + artificial lighting	Day lighting + artificial lighting	Day lighting + artificial lighting	Day lighting + artificial lighting
Activities	Very active as teaching involves physical activity	Attending lectures with light activities	Sitting and attending lectures + laboratory needs light to medium activity	Sitting and attending lectures + laboratory needs light to medium activity
Clothing	Clothing as judged by parents or elders	Restricted clothing and had to follow dress code	Restricted clothing and had to follow dress code	No specific dress code, free to adjust
Use of ICT	Almost no use	Less (demonstration purpose)	High (lectures)	Very high (lectures, laboratory)

AC: Air conditioned (HS + CS); NV: Naturally ventilated, ICT: Internet and communication technology

iv) *Cooling system (CS):* A classroom is constructed with the cooling system and during the study period cooling system was switched on.

v) *Air-condition (AC):* A classroom is constructed with heating and cooling system and during the study period either of the systems was switched on.

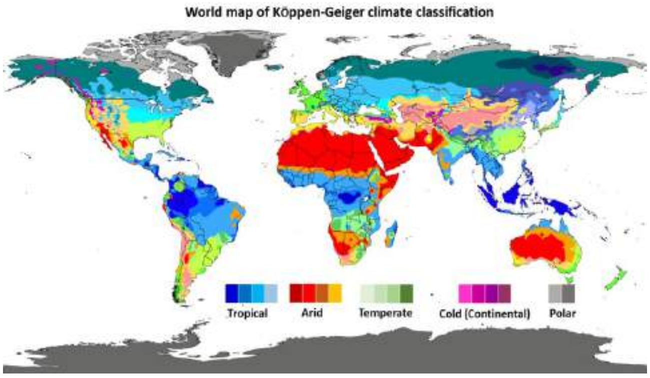
For the above-mentioned classifications, data such as sample size, time of the survey, geographic location, climate, operation mode of classrooms, comfort temperature, average clothing level, indoor air velocity and average outdoor temperature etc. were extracted from the research articles (the data listed in the form of tables and not provided here because of page constraints. But will be produced if asked by the reader). To analyze the data, it was decided to consider NV/FR classrooms and air-conditioned classrooms and club the studies accordingly for primary school, secondary school and university classrooms. It was found that in some of the research papers outdoor temperature data were not mentioned so online weather data source (mentioned in the reference list) was used to extract the data for the period in which the study was done. In this study, the proposed regression equations and adaptive thermal comfort models were analyzed in categories based on operation modes of classrooms. It was found that very few studies have proposed adaptive thermal comfort equations. Finally, a comparative analysis was carried out by plotting the comfort temperatures proposed in the studies on ASHRAE -55 2015 and CEN - 15251 standards (ASHRAE 55, 2013; CEN 15251, 2007; ISO-7730, 2005).

4 Discussion

4.1 Article types and publication trend

At all educational stages, functional requirement of the classroom is very distinct and so the student density in the classroom, indoor environment control, clothing choices, activity and use of internet and communication technology. Figures 3 and 4 show the Koppen-Geiger world climatic classification and the number of studies done in the classrooms of each climatic zone. It can be seen in Figure 4 that the distribution of studies is quite skewed. The highest number of studies is done in sub-tropical countries followed by countries in a temperate climate. Mediterranean and hot and dry climate countries have quite a few studies. Continent-wise, Asia and Europe lead the count. In Asia, maximum number of studies is being reported from Taiwan, China, and Malaysia. In Europe, maximum number of studies is being reported from UK, Italy, and Portugal. The approach followed by the researchers to carry out thermal comfort studies is also analyzed. Figure 5 represents the approach (PMV-PPD or adaptive thermal comfort methodology) followed in the studies carried out in different continents. It is clear that a maximum number of studies followed PMV-PPD methodology to evaluate the classroom thermal environment. To know about number of studies done for each educational stages classroom e.g. primary, secondary and university, figure 6 is plotted. It can be seen that highest number studies are done in primary and University classrooms in Europe and Asia respectively.

Publication trend of 81 articles is shown in Figure 1. It can be seen that highest number of articles are published in the year 2014 and 2015. The share of classroom thermal comfort studies in overall thermal comfort studies is only 0.49%. Figure 2 shows the increasing trend of publication with very high growth in last 10 years. To know the composition of the type of articles Figure 7 is plotted. It shows that in both the thermal comfort and thermal comfort in classrooms themes, original research papers dominate the publication followed by conference papers.



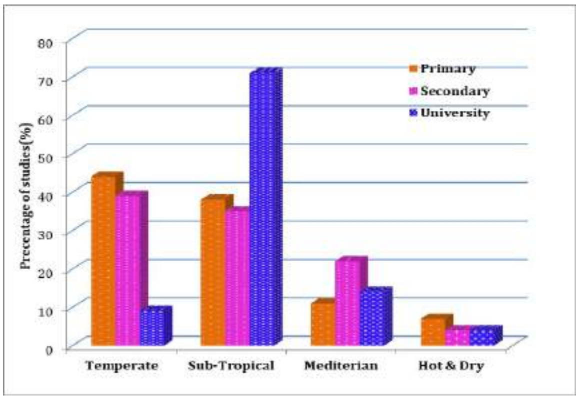
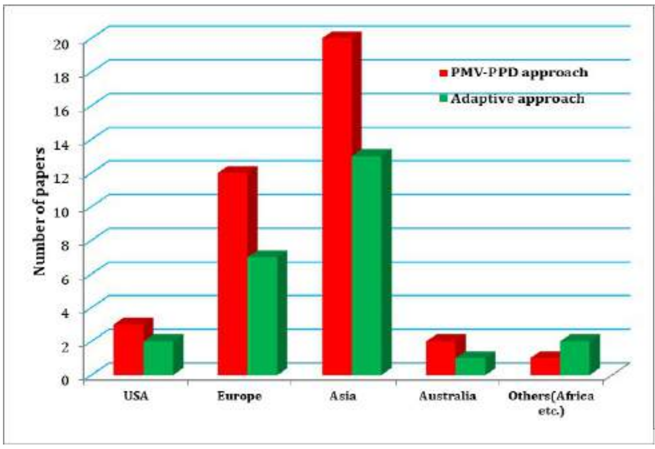


Figure 3 World map of Koppen-Geiger climate classification

Figure 4 Summary of thermal comfort studies conducted in different climates at various education level (total 81 articles)



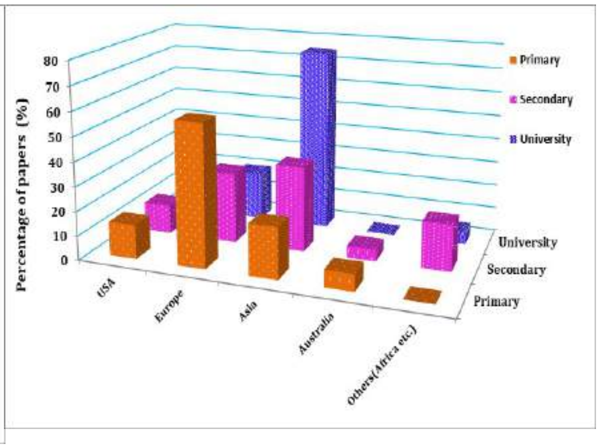


Figure 5 Distribution of papers considered for this review article following two schools of thoughts (PMV-PPD and adaptive approach: total 81 articles)

Figure 6 Classification of field studies conducted in classrooms based on education stages in different continents (total 81 articles)

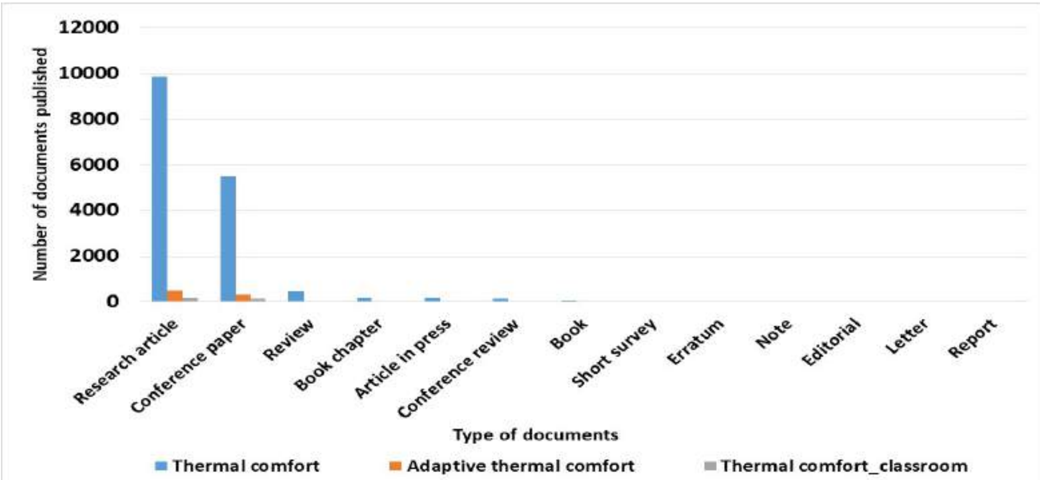


Figure 7 Type of documents on Scopus scientific database when search with keywords “thermal comfort, adaptive thermal comfort and thermal comfort in classroom” accessed on 7th August 2017

It is a healthy sign because it is enriching the database which is required to develop a robust thermal comfort model. It is also showing the increasing awareness and concern among the researchers and scientists about the IEQ and its role in the human well-being in different kind of built environments. A small number of classroom centric studies is a matter of concern despite knowing the impact of adequate IEQ on the learning ability of students and on his/her well-being. It demands more studies to be done across the globe so that a grand database can be built and it can be taken forward to the formulation of a new set of IEQ standards/guidelines for designing future classrooms.

4.2 Thermal comfort and preferences in primary school classrooms

All 81 research articles are classified into primary, secondary and university classrooms based studies. 28 out of 81 studies are carried out on primary school's classrooms (operated under either NV/FR or air-conditioned mode). Studies done on elementary and primary schools classrooms show a strong relationship between indoor thermal environment, student performance and well-being but lacks to put forth any direct evidence. It was also found that at this stage student do not take adaptive actions like changing clothing level, changing setpoint temperatures and opening and closing of windows on their own (Auliciems, 1975; Humphreys, 1977; Mors et al, 2011; Liu et al, 2016). At this grade student has to follow the choices of the adults for thermal environments. PMV and PPD methodology underestimate the actual thermal environments in both NV/FR and air-conditioned classrooms (Auliciems, 1975; Haddad et al, 2017). Studies also suggested that students at this stage are very active and have high metabolic rates compared to adults. Also, these students are always in the same uniform and seldom allowed to adjust despite the level of activity required in the classroom (Auliciems, 1975; Humphreys, 1977; Mors et al, 2011; Liu et al, 2016). Above all at this stage of education student's educational curricula demands many physical activities which aggravate the unacceptability of existing thermal environment (Auliciems, 1975; Humphreys, 1977; Mors et al, 2011; Liu et al, 2016).

4.3 Thermal comfort and preferences in secondary school classrooms

Total 27 research articles address the thermal comfort status and preferences in secondary school classrooms operated under NV/FR and air-conditioned modes. Like primary school classrooms, students at this stage are not satisfied with the existing thermal environment. Studies relating sustainability and energy efficiency concluded that in designing new classrooms or refurbishing old ones, more emphasis should be given adequate learning conditions which include non-thermal parameters too. It has been found that adequate learning conditions improve student's performance as much as 30% (Almeida et al, 2015; Almeida and de Freitas, 2015). At this stage also students in the classrooms prefer optimum temperature towards cooler side of the thermal sensation scale. Studies done in NV/FR classrooms concluded that students in summer months are more sensitive to change in temperature compared to winter months and neutral temperature in summer is considerably higher compared to winter months (Liang et al, 2012; Pereira et al, 2014; Puteha et al, 2012; Wargocki and Wyon, 2007).

4.4 Thermal comfort and preferences in university classrooms

University classrooms students have a greater degree of freedom to take adaptive actions to restore their comfort. Out of 81, 30 studies that are being carried out in university classrooms and are operated under NV/FR or air-conditioned mode. Study linking controls, adaptive actions and thermal comfort states that increasing level of control over microclimate and adaptive actions is directly related to enhanced satisfaction of the students towards the indoor thermal environment. Here also students preferred cool sensation in both NV and air-conditioned classrooms. So in winter months, when the heating system is required to run then set temperature can be kept low and this will save heating energy consumption by 12% (Jung et al, 2011). In case of university student's, they move in and out of the classroom after every class. So they are in transient condition for about 20-30% of the time if a class is of 1-hour duration. So the memory of the previous environment greatly affects the thermal comfort and preference of a student in university classrooms. This happens several times in a day, during their stay in the university. In-classroom students experience a transient thermal condition for first 10-15 minutes in a class and when ISO 7730, ASHRAE 55 and CEN 15251 standard which generally deals with steady-state conditions, applied to evaluate classrooms thermal environment, the deviation reported by many studies seems obvious (ISO 7730, 2005; ASHRAE 55, 2013; CEN 15251, 2007; Cheng et al, 2008; Cao et al, 2011; Wang et al, 2014; Wang et al, 2017). Here also it is the case where standards are applied to design an environment whose functionality and the requirement is quite different to the mandate of the standard.

4.5 Regression equations and operation modes of classrooms

Based on above classification the studies which have proposed regression equations were segregated. Table 2 presents the list of regression equations for primary, secondary and university classrooms. These equations are establishing the relationship between mean thermal sensation and indoor temperature (operative temperature, air temperature or globe temperature). To find the change in temperature required to shift in one thermal sensation vote, the inverse of the coefficient attached to mean thermal sensation is calculated. On analyzing these values, it is found that very few studies are able to give reliable value. A temperature change of up to 5 °C to shift one sensation vote seems in good agreement with other thermal comfort studies. It is strange that values in the range of 7 °C to 22 °C are being found.

Regression equations proposed by studies in classrooms are analyzed where the heating and cooling system is operational during the study period. Studies that proposed the regression equation are listed in Table 3. Again analyzing the temperature change required to shift one thermal sensation vote, we find that in this case, the values are more reliable compared to NV and FR classrooms except for 3 studies. On analyzing mixed mode operated classrooms we find that a maximum number of studies in all the categories show high-temperature change to shift one thermal sensation vote. Table 4 presents the details of the studies and calculated values. From Tables 2, 3 and 4 it is evident that in most of the classrooms studies the results obtained are quite different from what thermal comfort study reveals when done in a built environment other than classrooms. This also concludes that the students in the classrooms were highly unsatisfied with the existing indoor environmental conditions.

Table 2 Proposed Regression equations by the comfort studies done in naturally ventilated and free running primary, secondary and university classrooms

Classroom	Reference	Country	Building type	Operation type	Survey period	Regression equation	Temperature change required to shift one thermal sensation (°C)
Primary	Hwang et al., 2009	Central, Taiwan	NV	FR	Sept 2005 to Jan 2006	$MSV = 0.01T_{op} - 0.30$	10
	Teli D et al., 2012	Hampshire, England, UK	NV	FR	Mar to Aug 2011	$TSV = 0.26T_{op} - 5.68$	3.85
	Teli et al., 2013	Southampton, UK	HS + CS	FR	Apr to Jul 2011	M: $TSV = 0.27T_{op} - 5.56$; F: $TSV = 0.25T_{op} - 5.48$	M= 3.7; F= 4
	Yun et al., 2014	Seoul, Korea	HS + CS	FR	Apr to Jun 2013	$TSV = 0.29T_{op} - 6.47$	3.45
	Liu et al., 2016	Weinan and Wuwei, China	HS + CS	FR	Nov and Dec 2014	$TSV_m = 0.18\ T_{op} - 2.72$	5.56
Secondary	Hwang et al., 2009	Central, Taiwan	NV	FR	Sept 2005 to Jan 2006	$MSV = 0.01T_{op} - 0.30$	10
	Liu et al., 2016	Northwestern China	HS + CS	FR	Nov and Dec 2014	$TSV_m = 0.18\ T_{op} - 2.72$	5.56
University	Zhang et al., 2007	Hunan University, China	NV	FR	Mar to Apr 2005	$TSV = 0.045T_{op} - 0.96$; $PMV = 0.116T_{op} - 2.88$	TSV= 22.2; PMV= 9.1
	Cheng et al., 2008	Central Taiwan	NV	FR	Apr to Nov 2006	$TSV = 0.34T_{op} - 8.4$	2.94
	Wang et al., 2014	Harbin, China	HS + CS	FR	Dec 2015-Jan 2015, Apr 2011	$TSV_{spr} = 0.15T_a - 3.32$	6.67
	Mishra & Ramgopal, 2014_1	Kharagpur, India	NV	FR	Jan to Apr 2013	$TSV = 0.14T_{op} - 3.72$	7.14
	Mishra & Ramgopal, 2014_2	Kharagpur, India	NV	FR	Jan to Apr 2013	$TSV = 0.14T_{op} - 3.72$	7.14
	Baruah et al., 2014	Tezpur, India	NV	FR	Feb and May 2013	$TSV = 0.24T_{in} - 5.73$	4.16
	Vittal et al., 2016	Tamil Nadu, India	NV	FR	Dec 2014 and Jan 2015	$TSV = 0.54T_g - 15.59$	1.85

NV: Naturally ventilated; FR: Free running; T_c: Comfort temperature; T_{op}: Operative temperature; T_a: Air temperature; TSV: Thermal sensation vote; MSV: Mean sensation vote; T_{in}: Indoor air temperature; TSV: Thermal sensation vote; TSV_m: Mean thermal sensation vote; PMV: Predicted mean vote; M: Male; F: Female; TSV_{spr}: Spring season thermal sensation vote; AC: Air conditioned (HS + CS)

Table 3 Proposed regression equations by the comfort studies done in heating and cooling system operated primary, secondary and university classrooms

Classrooms	Reference	Country	Building type	Operation type	Survey period	Regression equation	Temperature change required to shift one thermal sensation (°C)
Primary	Auliciems, 1975	Queensland, Australia	HS + CS	HS	May to Aug 1973	$TSV = 0.147T_{in} – 3.6$	6.8
Secondary	Auliciems, 1969	Reading, UK	HS + CS	HS	Jan to Apr 1967; Oct 1967; Mar 1968	$TSV = 0.12T_{in} – 7.72$	8.33
	Auliciems, 1975	Queensland, Australia	HS + CS	HS	May to Aug 1973	$TSV = 0.15T_{in} – 3.6$	6.67
University	Cheng et al., 2008	Central Taiwan	HS + CS	CS	Apr to Nov 2006	$TSV_{AC} = 0.35T_{op} – 8.8$	2.86
	Wang et al., 2014	Harbin, China	HS + CS	HS	Dec 2015-Jan 2015, Apr 2011	$TSV_{win} = 0.24T_a – 5.43$	4.17
	Wang et al., 2016	Harbin, China	HS + CS	HS	Oct 2013 to Apr 2014	$TSV_m = 0.16T_{in} – 2.97$	6.25
	Zaki et al., 2017	Mara, My; Kyushu, Jp	HS + CS	CS	Jp: Feb to Mar 2013; My: Mar to May 2013	My: $TSV_{cl} = 0.33T_{op} – 8.8$; Jp: $TSV_{cl} = 0.43T_{op} – 11.2$	My: 3.03; Jp: 2.33

CS: Cooling system; HS: Heating system; T_{op}: Operative temperature; T_a: Air temperature; T_{in}: Indoor air temperature; TSV: Thermal sensation vote; TSV_m: Mean thermal sensation vote; ; TSV_{win}: Winter thermal sensation vote; ; TSV_{AC}: Thermal sensation vote in air-conditioned classroom; My: Malaysia; Jp: Japan; AC: Air conditioned (HS + CS)

Table 4 Proposed Regression equations by the comfort studies done in mixed mode operated primary, secondary and university classrooms

Classroom	Reference	Country	Building type	Operation type	Survey period	Regression equation	Temperature change required to shift one thermal sensation (°C)
Primary	de Dear et al., 2015	Sydney, Australia	HS + CS	FR + HS + CS + EC	Sum 2013	$TSV_m = 0.12\ T_{op} – 2.78$	8.33
	Trebilcock et al., 2017	Shiraz, Iran	HS + CS	HS+ EC+ FR	Aut, Win and Warm 2012 - 2013	$TSV_m = 0.27\ T_{op} – 6.25$	3.7

Secondary	Kwok, 1997	Hawaii, USA	HS + CS	FR + HS + CS	Sept-Oct 1995; Jan - Feb 1996	$TSV = 0.29T_{op} - 7.40$	3.45
	de Dear et al., 2015	Sydney, Australia	HS + CS	FR + HS + CS + EC	Sum 2013	$TSV_m = 0.12 T_{op} - 2.78$	8.33
University	Hwang R-L et al., 2006	Centre and South, Taiwan	HS + CS	FR + CS	Sum 2003, Sum 2004	$TSV = 0.14ET - 3.76$; $PMV = 0.28ET - 7.72$	TSV= 7.14; PMV= 3.57
	Hu et al., 2006	Wuhan, China	HS + CS	FR + CS + HS	Jun to Sept and Dec to Feb	$TSV = 0.13ET - 2.93$	7.7 ET
	Buratti & Ricciardi, 2009	Perugia, Terni, Pavia and Italy	HS + CS	HS + CS	Nov to Dec 2004, Feb, Mar & May 2005	$PMV = 0.16T_{op} - 3.31$	7.69
	Mishra & Ramgopal, 2015	Kharagpur, India	HS + CS	FR + CS	Aug to Oct 2013	$TSV = 0.14T_{op} - 3.72$	7.14
	Zaki et al., 2017	Mara, My; Kyushu, Jp	HS + CS	FR + CS	Jp: Feb to Mar 2013; My: Mar to May 2013	My: $TSV_{cl} = 0.33T_{op} - 8.8$; Jp: $TSV_{cl} = 0.43T_{op} - 11.2$	My: 3.03; Jp: 2.33

NV: Naturally ventilated; CS: Cooling system; HS: Heating system; EC: Evaporative cooling; ET: Effective temperature; T_{op}: Operative temperature; TSV: Thermal sensation vote; TSV_m: Mean thermal sensation vote; PMV: Predicted mean vote; My: Malaysia; Jp: Japan; AC: Air conditioned (HS + CS)

Table 5 Proposed adaptive comfort equations by the comfort studies done in primary, secondary and university classrooms

Classroom	Reference	Country	Building type	Operation type	Survey period	Adaptive comfort equation
Primary	Liang et al., 2012	Taichung, Taiwan	NV	FR	Sept 2005 to Feb 2006	$T_c = 0.62T_{om} + 12.1$
	Huang et al., 2015	Central Taiwan	NV	FR	May, Jun, Sept and Oct 2013	$T_c = 0.33T_{rm} + 18.8$
	Trebilcock et al., 2017	Santiago, Chile	NV	FR	Jul-Aug 2013 and Nov -Dec 2014	$T_c = 0.834T_{rm} + 7.11$
Secondary	Liang et al., 2012	Taichung, Taiwan	NV	FR	Sept 2005 to Feb 2006	$T_c = 0.62T_{om} + 12.1$
University	Yao et al., 2010	Chongqing, China	NV	FR	Mar 2005 to May 2006	$T_c = 0.6T_{out} + 9.85$
	Jung et al., 2011	Busan, South Korea	HS + CS	HS + CS + FR	Mar to Jun 2009, Sept to Dec 2009	$T_c = 0.42T_{om} + 16.90$

NV: Natural Ventilation; FR: Free running; HS: Heating system; CS: Cooling system; T_{om}: Outdoor monthly mean temperature; T_c: Comfort temperature; T_{rm}: Running mean comfort temperature over two days; T_{out}: Outdoor temperature; AC: Air conditioned (HS + CS)

Very interestingly it can be said that this study did not succeed to find the consistency between the temperature change required to shift one thermal sensation vote in classrooms at different education stages and under different operation modes.

Table 5 presents the adaptive comfort equations proposed by six studies done in primary, secondary and university classrooms altogether. Most of the studies have comparable slope except the study done in Santiago, Chile. This study proposes very steep slope stating that subjects were very sensitive to temperature change.

4.6 Adaptive comfort equations

In this study, comfort temperatures proposed by different studies are plotted on ASHRAE 55-2013 and CEN 15251-2007 comfort band. To draw this plot, proposed comfort temperature and daily mean outdoor temperature data are extracted from the selected research articles. In some research articles where the daily outdoor mean temperature was not provided, a web source was used to get the data of that location for the study period (Metoffice, 2017). Figures 8 and 9 present the plots of comfort temperature on ASHRAE -55 and CEN 15251 comfort band **(**ASHRAE 55, 2013; CEN 15251, 2007; ISO 7730, 2005**)**. On carrying out regression analysis we get four adaptive comfort equations, one each for primary, secondary, university classrooms and all classrooms (considering primary, secondary and university together).

$$T_{cop\_pri} = 0.28T_{out} + 17.02\ (N = 17;\ R^2 = 0.21) \quad (1)$$

$$T_{cop\_sec} = 0.46T_{out} + 14.33\ (N = 16;\ R^2 = 0.75) \quad (2)$$

$$T_{cop\_uni} = 0.36T_{out} + 15.53\ (N = 13;\ R^2 = 0.48) \quad (3)$$

$$T_{cop\_all} = 0.36T_{out} + 15.77\ (N = 46;\ R^2 = 0.52) \quad (4)$$

Where T_{cop_pri} is comfort temperature (operative temperature) in primary school classroom

T_{cop_sec} is comfort temperature (operative temperature) in secondary school classroom

T_{cop_uni} is comfort temperature (operative temperature) in university classroom

T_{cop_all} is comfort temperature (operative temperature) in all classrooms

and T_{out} is daily mean outdoor temperature

It is interesting to note that student at all the educational stages has a different level of sensitivity towards outdoor temperature change. Out of all the stages, primary school students are least sensitive to temperature change. This conclusion is supported by several studies and primarily Humphreys (Humphreys, 1973; Humphreys, 1977) and Auliciems (Auliciems, 1969; Auliciems, 1972, Auliciems, 1973; Auliciems, 1975). This happens because the clothing level selection for this section of students is primarily adult dependent. Out of three levels, the most sensitive to the outdoor change of temperature are secondary school students. Because they have limited scope of clothing variation because they have to wear school uniform throughout the year irrespective of the type of activity they have to perform based on school curricula (limited scope of clothing related adaptation). University students show the slope which is very close to ASHRAE standard and CEN standard because the database used to propose these comfort bands consists of adults subjects and the university students are in the age bracket of adults. Moreover, college students have maximum liberty and flexibility out of three educational stages for adaptation as listed in Table 1. When all comfort temperature of all stage classrooms is plotted together on ASHRAE comfort band it resulted in equation 4. Figure 10 shows the plot all neutral temperature on ASHRAE comfort band. Regression line shows that the slope is similar to that of ASHRAE standard. But this picture is quite different to that of what was found when each primary, secondary and university classroom plotted individually. The range of comfort temperatures is estimated by finding out lowest and highest reported neutral temperatures in the primary, secondary and university classrooms in each continent. For this plot operation mode of classrooms are not considered. Figure 11 is showing the range of comfort temperature for primary, secondary and university classrooms. It shows that among all the continents, university classrooms in Asia are showing a highest band of comfort temperatures.

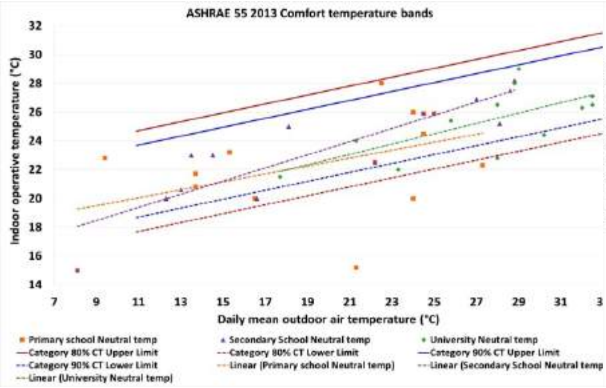


Figure 8 Plot of neutral temperature proposed by studies carried out in primary school, secondary school and university classrooms separately on ASHRAE comfort bands

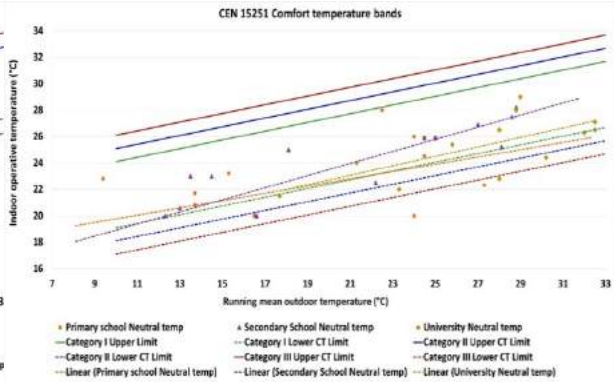


Figure 9 Plot of neutral temperature proposed by studies carried out in primary school, secondary school and university classrooms separately on CEN comfort bands

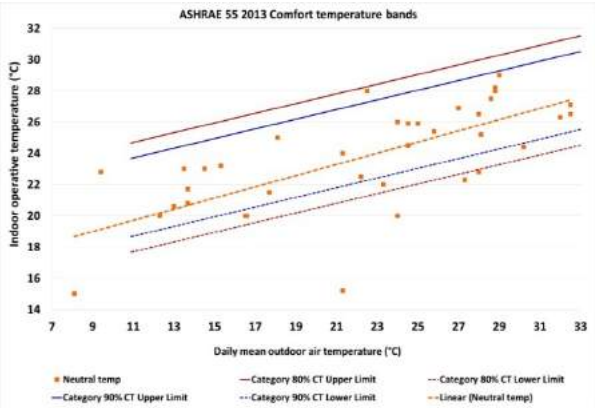


Figure 10 Plot of neutral temperature proposed by studies carried out in primary school, secondary school and university classrooms together on ASHRAE comfort bands

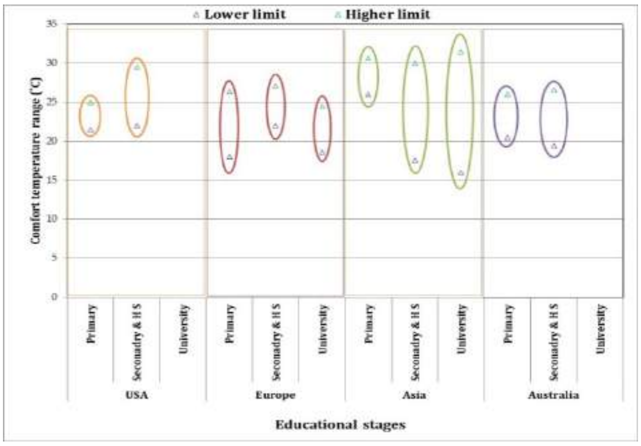


Figure 11 Comfort temperature bandwidth in different continents proposed by research articles considered in this study (total 81 articles)

Indoor air quality consideration is not the prime objective of this study but it was found that most of the studies reported quite a high level of CO_2 concentration (up to 3000 ppm) in the classrooms (Almeida et al, 2015; Stazia et al, 2017). Most of the studies also pointed out high density and lack of adequate ventilation as the probable reasons for the high level of CO_2 concentration in classrooms (poor indoor air quality) (Almeida et al, 2015; Stazia et al, 2017).

5 Conclusions and ways forward

This study on thermal comfort in the classroom has led to the following conclusions:

- Students in all classrooms at all stages of their education, i.e. primary, secondary and at university, report feeling comfortable on the cooler side of the thermal sensation scale. Primary school students are least sensitive to outdoor temperature changes.
- In case of naturally ventilated classrooms, outdoor climatic conditions have a stronger influence on indoor thermal conditions. Neutral temperatures in NV classrooms are higher in summer than in winter.
- Studies done in NV/FR classrooms concluded that students in summer months are more sensitive to change in temperature compared to winter months and their thermal perception was strongly affected by acclimatization.
- In designing new classrooms and retrofitting old classrooms it is now required to change the priority of providing an adequate learning environment
- Secondary school and university students are in a position to express their thermal sensation experiences and are in a better position to make day to day adjustments like changing clothing level, opening/closing of windows and switch on/off ceiling fans. These adjustments play a significant role in defining the thermal acceptability in the NV classrooms.
- In recent publications over last 10-15 years, it can be seen that both PMV-PPD and adaptive methodology are simultaneously used by researchers with more emphasis on the adaptive methodology to assess the classrooms thermal environment.
- Some studies able to show the qualitative relationship between IEQ and IAQ on student academic performance and well-being. Still, this needs more research where the performance and wellbeing can be quantified. Different authors follow different methodology leading to difficulty in drawing conclusions. If the methodology is standardized then it will help in quantifying performance and wellbeing of students in classrooms.
- In air-conditioned classrooms in the winter season, it was found that students feel comfortable a lower temperature so heating system temperature can be set low temperature as it leads to saving of about 10% heating energy consumption without compromising on thermal comfort.
- Classrooms are functionally quite different compared to other built environments like offices and residences. Unavailability of classroom related guidelines making designers and engineers consider classrooms as any other built environment which is failing its intended purpose of providing an adequate learning environment.
- Naturally ventilated classrooms fair better compared to air-conditioned classrooms as they have a lower CO_2 level. Reason for this is attributed to lower ventilation rate and high density of students in air-conditioned classrooms.
- A study done by Kruger et al concludes that Nonclassroom factors such as visibility, acoustics, and furniture's also affected classroom comfort.
- Very interestingly this study did not succeed to find the consistency between the temperature change required to shift one thermal sensation vote in classrooms at different levels and under different operation modes. Though a temperature change of up to 5 °C to shift one sensation vote seems in good agreement.
- Comfort temperatures given by the selected studies are being used to develop adaptive comfort equations to estimate indoor comfort temperature in primary, secondary and university classrooms.

Number of research articles published related to thermal comfort study in classrooms are very less compared to thermal comfort study in general. It is seen that the research trend in terms of publication is increasing in last few years and it is a good sign because it shows the awareness and growing concern about the student's performance and well-being in classrooms. The research gaps mentioned in the introduction section still remains valid but some progress can be seen in the form of different approach being adopted by researchers to cover most of the aspects that affects the performance and well-being of students in the classroom. The biggest limitation is this direction is the number of studies as often field studies face the challenge of accessibility and reliable data collection. Since it is very difficult to cover all aspects of comfort in a single study and this limitation can be overcome by increasing the number of studies thus increasing the possibility to cover most of the aspects of thermal comfort. Moreover, this study successfully brings forth the evidence that the new classroom design or refurbishing the existing ones need a separate set of guidelines or standards because existing comfort standards and design guidelines are inadequate. Also, it is required to establish a standard methodology and protocol regarding data collection and instrumentation for studies being conducted in classrooms. Different methodology and instrumentation make it difficult to combine the data collected in different studies and analyze them quantitatively linking performance, wellbeing, thermal comfort.

Acknowledgements

This research is funded by the Japan Society for Promotion of Sciences (JSPS) postdoctoral research grant.

References

Almeida R.M.S.F., de Freitas V.P., 2015. *IEQ assessment of classrooms with an optimized demand controlled ventilation system, Energy Procedia, 78: 3132 – 3137.*

Almeida R.M.S.F., de Freitas V.P., Delgado J.M.P.O., 2015. *Indoor Environmental Quality in Classrooms: Case Studies, pp: 31-55, Springer International Publishing AG Switzerland, ISBN 978-3-319-15359-9*

Al-Rashidi K., Loveday D., Al-Mutawa N., 2012. *Impact of ventilation modes on carbon dioxide concentration levels in Kuwait classrooms. Energy Buildings, 47: 540–549.*

ASHRAE, 2013. *Thermal environmental conditions for human occupancy, ANSI/ASHRAE standard 55-2013.*

Auliciems A., 1969. *Thermal requirements of secondary schoolchildren in winter, The Journal of Hygiene. 67: 59-65.*

Auliciems A., 1972. *Classroom Performance as a Function of Thermal Comfort, International Journal of Biometeorology. 16, 233-246.*

Auliciems A., 1973. *Thermal sensations of secondary schoolchildren in summer, The Journal of Hygiene. 71: 453-458.*

Auliciems A., 1975. *Warmth and comfort in the subtropical winter: a study in Brisbane schools, The Journal of Hygiene. 74: 339-343.*

Auliciems A., 1981. *Towards a psycho-physiological model, Int. J. Biometeorol. 25: 109–122.*

Barrett P., Zhang Y., Moffat J., Kobbacy K., 2013. *A holistic, multi-level analysis identifying the impact of classroom design on pupils' learning, Building and Environment, 59: 678-689.*

Baruah, P., Singh M.K., Mahapatra S., 2014. *Thermal Comfort in Naturally Ventilated Classrooms, PLEA -2014 Conference, December 16 – 18, Ahmadabad, Gujarat, India.*

Brager G.S., de Dear R.J., 1998. *Thermal adaptation in the built environment: a literature review, Energy and Buildings, 27: 83–96.*

Buratti C., Ricciardi P., 2009. *Adaptive analysis of thermal comfort in university classrooms: Correlation between experimental data and mathematical models, Building and Environment, 44: 674-687.*

Cao B., Zhu Y., Ouyang Q., Zhou X., Huang L., 2011. *Field study of human thermal comfort and thermal adaptability during the summer and winter in Beijing., Energy and Buildings, 43: 1051–1056.*

CEN EN 15251, 2007. *Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, European Committee for Standardization, Brussels, Belgium.*

Cheng, M.J., Hwang, R.L., Lin, T.P., 2008. *Field Experiments on Thermal Comfort Requirements for Campus Dormitories in Taiwan. Indoor and Built Environment, 53: 191-202.*

Choi, S.M., Guerin D.A., Kim H.U., Brigham J.K, Bauer T., 2013. *Indoor Environmental Quality of Classrooms and Student Outcomes: A Path Analysis: Approach, Journal of Learning Spaces, 2:2.*

de Dear R.J., Akimoto T., Arens E.A., Brager G., Candido C., Cheong K.W.D., Li B., Nishihara N., Sekhar S.C., Tanabe S., Toftum J., Zhang H., Zhu Y., 2013. *Progress in thermal comfort research over the last twenty years, Indoor Air, 23: 442–461.*

de Dear R.J., Brager G.S., 1998. *Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions, 104: 145-167.*

de Dear R.J., Kim J., Candido C., Deuble M., 2015. *Adaptive thermal comfort in Australian school classrooms, Building Research & Information, 43: 383-398.*

Di Perna C., Stazi F., Casalena A.U., D'Orazio M., 2011. *Influence of the internal inertia of the building envelope on summertime comfort in buildings with high internal heat loads. Energy and Buildings, 43: 200–206.*

Djongyang N., Tchinda R., Njomo D., 2010. *Thermal comfort: a review paper., Renewable, and Sustainable Energy Reviews, 14: 2626–2640.*

Fanger P.O., 1970. *Thermal comfort. Analysis and applications in environmental engineering. Copenhagen: Danish Technical Press.*

Fanger P.O., Toftum J., 2002. *Extension of the PMV model to non-air-conditioned buildings in warm climates, Energy and Buildings, 34: 533–536.*

Feriadi H., Wong N.H., 2004. *Thermal comfort for naturally ventilated houses in Indonesia. Energy and Building, 36: 614 -626.*

Fong M.L., Hanby V., Greenough R., Lin Z., Cheng Y., 2015. *Acceptance of thermal conditions and energy use of three ventilation strategies with six exhaust configurations for the classroom. Building and Environment, 94: 606–619.*

Gao J., Wargocki P., Wang Y., 2014. *Ventilation system type, classroom environmental quality and pupils' perceptions and symptoms. Building and Environment, 75: 46– 57.*

Giuli V.De., Pos O Da., Carli M.De., 2012. *Indoor environmental quality and pupil perception in Italian primary schools, Building and Environment, 56: 335-345.*

Giuli V.De., Zecchin R., Corain L., Salmaso L., 2015. *Measurements of indoor environmental conditions in Italian classrooms and their impact on children's comfort, Indoor and Built Environment, 24: 689–712.*

Haddad S., Osmond P., King S., 2017. *Revisiting thermal comfort models in Iranian classrooms during the warm season, Building Research & Information, 45: 457-473.*

Hoof J.V., 2008. *Forty years of Fanger's model of thermal comfort: comfort for all?, Indoor Air, 18: 182–201.*

Hu P.F., Liu W., Jiang Z.N., 2006. *Study on the indoor thermal sensation of young college students in the area which is hot in summer and cold in winter. International Journal of Architectural Science, 7: 47–52.*

Huang K.T., Huang W.P., Lin T.P., Hwang R.L., 2015. *Implementation of green building specification credits for better thermal conditions in naturally ventilated school buildings, Building and Environment,* 86: *141-150.*

Huang K.T., Hwang R.L., 2016. *Parametric study on energy and thermal performance of school buildings with natural ventilation, hybrid ventilation and air conditioning, Indoor and Built Environment, 25: 1148–1162.*

Humphreys M.A., 1975. *Field studies of thermal comfort compared and applied, Symposium on physiological requirements of the microclimate, Prague, 8-10 September.*

Humphreys M.A., 1977. *A Study of the Thermal Comfort of Primary School Children in Summer, Building and Environment, 12: 231-239.*

Humphreys M.A., 1978. *Outdoor temperatures and comfort indoors, Building Research and Practice. 6: 92-105.*

Humphreys M.A., Nicol J.F., 1998. *Understanding the adaptive approach to thermal comfort. ASHRAE Trans. 104: 991-1004.*

Humphreys, M.A., 1973. *Classroom temperature, clothing and thermal comfort-A study of secondary school children in the summertime. Building Services Engineer, 41: 191-202.*

Hwang, R. L., Lin, T. P., Chen, C. P. & Kuo, N. J., 2009. *Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan. International Journal of Biometeorology, 53: 189-200.*

Hwang, R.L., Lin, T-P., Kuo N.J., 2006*. Field experiments on thermal comfort in campus classrooms in Taiwan. Energy and Buildings, 38: 53-62.*

ISO 7730: 2005. *Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, International Organization for Standardization, 2005.*

Jung G., Song S.ki., Ahn Y.C., Oh GS., Im Y.B., 2011. *Experimental research on thermal comfort in the university classroom of regular semesters in Korea, Journal of Mechanical Science and Technology, 25: 503-512.*

Karjalainen S., 2012. *Thermal comfort and gender: a literature review, Indoor Air, 22: 96–109.*

Karyono T.H., 2000. *Report on thermal comfort and building energy studies in Jakarta, Indonesia. Building and Environment, 35: 77-90.*

Katafygiotou M.C., Serghides D.K., 2014. *Indoor comfort and energy performance of buildings in relation to occupants' satisfaction: investigation in secondary schools of Cyprus, Advances in Building Energy Research, 8: 216-240.*

Kr'uger E.L., Zanninb Paulo H.T. 2004. *Acoustic, thermal and luminous comfort in classrooms, Building and Environment, 39: 1055 – 1063.*

Kwok A.G., 1998. *Thermal comfort in tropical classrooms. ASHRAE Transactions, 104: 1031-50.*

Lee M.C., Mui K.W., Wong L.T., Chan W.Y., Lee E.W.M., Cheung C.T., 2012. *Student learning performance and indoor environmental quality (IEQ) in air-conditioned university teaching rooms, Building and Environment 49: 238-244.*

Liang, H.H., Lin T.P. Wang R.L., 2012. *Linking occupants' thermal perception and building thermal performance in naturally ventilated school buildings. Applied Energy, 94: 355-363.*

Liu Y., Jiang J., Wang D., Liu J., 2016. *The indoor thermal environment of rural school classrooms in Northwestern China, Indoor and Built Environment, 0: 1–18.*

Mallick F.H., 1996. *Thermal comfort and building design in the tropical climates. Energy and Buildings, 23: 161-167.*

Martinez-Molina A., Boarin P., Tort-Ausina I., Vivancos J_e-Luis., 2017. *Post-occupancy evaluation of a historic primary school in Spain: Comparing PMV, TSV and PD for teachers' and pupils' thermal comfort, Building and Environment, 117: 248-259.*

McCartney K.J., Nicol J.F., 2002. *Developing an adaptive control algorithm for Europe, Energy and Buildings, 34: 623–635.*

Mendell M.J., Heath G.A., 2005. *Do indoor pollutants and thermal conditions in school's influence student performance? A critical review of the literature, Indoor Air, 15: 27–52.*

Metoffice., 2017. *http://www.metoffice.gov.uk/public/weather/climate/ accessed on 15th September.*

Mishra A., Ramgopal M., 2014. *Thermal comfort field study in undergraduate laboratories–An analysis of occupant perceptions, Building and Environment, 76: 62-72.*

Mishra A., Ramgopal M., 2014. *Thermal comfort in undergraduate laboratories - A field study in Kharagpur, India, Building and Environment, 71: 223-232.*

Mishra A.K, Ramgopal M., 2013. *Field studies on human thermal comfort -An overview, Building and Environment, 64: 94-106.*

Mishra A.K., Derks M.T.H., Kooi, L., Loomans, M.G.L.C., Kort, H.S.M., 2017. *Analysing thermal comfort perception of students through the class hour, during the heating season, in a university classroom, Building and Environment, 125: 464-474.*

Mors, S. T., Hensen, J.L.M., Loomans, M.G.L.C., Boerstra, A.C., 2011. *Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts. Building and Environment, 46: 2454-2461.*

Nam I., Yang J., Lee D., Park E., Sohn J-R., 2015. *A study on the thermal comfort and clothing insulation characteristics of preschool children in Korea. Building and Environment, 92: 724–733.*

Nico M.A, Liuzzi S., Stefanizzi P., 2015. *Evaluation of thermal comfort in university classrooms through objective approach and subjective preference analysis, Applied Ergonomics, 48: 111-120.*

Nicol J.F., 2004. *Adaptive thermal comfort standards in the hot–humid tropics, Energy and Buildings, 36: 628–637.*

Nicol J.F., Humphreys M.A., 2002. *Adaptive thermal comfort and sustainable thermal standards for buildings, Energy and Buildings, 34: 563–572.*

Nicol J.F., Humphreys M.A., 2002. *Adaptive thermal comfort and sustainable thermal standards for buildings, Energy and Buildings, 34: 563–572.*

Pereira L.D., Raimondo D., Corgnati S.P., da Silva M.G., 2014. *Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: Methodology and results, Building and Environment, 81: 69-80.*

Puteha M., Ibrahimb M.H, Adnana M., Ahmad C.N.C., Nohc N.M., 2012. *Thermal comfort in classroom: constraints and issues, Procedia - Social and Behavioural Sciences, 46: 1834 – 1838.*

Serghides D.K., Chatzinikola C.K., Katafygiotou M.C., 2015. *Comparative studies of the occupants' behaviour in a university building during winter and summer time, International Journal of Sustainable Energy, 34: 528-551.*

Stazia F., Naspib F., Ulpianic G., Di Perna C., 2017. *Indoor air quality and thermal comfort optimization in classrooms developing an automatic system for windows opening and closing, Energy and Buildings, 139: 732–746.*

Taleghani M., Tenpierik M., Kurvers S., Dobbelsteen A van den., 2013. *A review into thermal comfort in buildings, Renewable and Sustainable Energy Reviews, 26: 201–215.*

Teli D., James P.A.B., Jentsch M.F., 2013. *Thermal comfort in naturally ventilated primary school classrooms, Building Research & Information, 41: 301-316.*

Teli D., Jentsch M.F., James P. A.B., 2012. *Naturally ventilated classrooms: An assessment of existing comfort models for predicting the thermal sensation and preference of primary school children, Energy and Buildings, 53: 166-182.*

Teli D., Jentsch MF., James P.A.B., 2014. *The role of a building's thermal properties on pupils' thermal comfort in junior school classrooms as determined in field studies, Building and Environment, 82: 640-654.*

Turunena M., Toyinboa O., Putusb T., Nevalainena A., Shaughnessyc R., 2014. *Haverinen-Shaughnessyaa U., Indoor environmental quality in school buildings, and the health and well-being of students, International Journal of Hygiene and Environmental Health, 217: 733–739.*

Wang Z., Li A., Ren J., He Y., 2014. *Thermal adaptation and thermal environment in university classrooms and offices in Harbin, Energy and Buildings, 77: 192–196.*

Wang Z., Ning H., Zhang X., Ji Y., 2017. *Human thermal adaptation based on university students in China's severe cold area, Science and Technology for the Built Environment, 23: 413-420.*

Wargocki P., Wyon D.P., 2007. *The Effects of Moderately Raised Classroom Temperatures and Classroom Ventilation Rate on the Performance of Schoolwork by Children (RP-1257), HVAC&R Research, 13: 193-220.*

Wargocki P., Wyon D.P., 2013. *Providing better thermal and air quality conditions in school classrooms would be cost-effective, Building and Environment, 59: 581-589.*

Wong N.H., Feriadi H., Lim P.Y., Tham K.W., Sekhar C., Cheong K.W., 2002. *Thermal comfort evaluation of naturally ventilated public housing in Singapore. Building and Environment, 37: 1267-1277.*

Wong N.H., Khoo S.S., 2003. *Thermal Comfort in classrooms in the tropics. Energy and Buildings, 35: 337-51.*

Yang L., Yan H., Lam J.C., 2014. *Thermal comfort and building energy consumption implications –A review, Applied Energy, 115: 164–173.*

Yang Z., Becerik-Gerber B., Mino L., 2013. *A study on student perceptions of higher education classrooms: Impact of classroom attributes on student satisfaction and performance, Building and Environment, 70: 171-188.*

Yau Y.H., Chew B.T., 2014. *A review on predicted mean vote and adaptive thermal comfort models, Journal of Building Services Engineering Research & Technology, 35: 23–35.*

Yun H., Nam I., Kim J., Yang J., Lee K., Sohn J., 2014. *A field study of thermal comfort for kindergarten children in Korea: An assessment of existing models and preferences of children, Building and Environment, 75: 182 - 189.*

Zaki S.A., Damiati S.A., Rijal H.B., Hagishima A., Razak A.A., 2017. *Adaptive thermal comfort in university classrooms in Malaysia and Japan, Building and Environment, 122: 294-306.*

Zhang G., Zhenga C., Yanga W., Zhanga Q., Moschandreasa D.J., 2007. *Thermal Comfort Investigation of Naturally Ventilated Classrooms in a Subtropical Region, Indoor and Built Environment, 16: 148–158.*

Zomorodian Z.S, Tahsildoost M., Hafezi M., 2016. *Thermal comfort in educational buildings: A review article, Renewable and Sustainable Energy reviews, 59: 898-906.*

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Thermal comfort in classrooms in Mexico´s hot and humid climate

Maella González Cetz[1], Gabriel Gómez Azpeitia[2]

[1] Facultad de Arquitectura, Universidad Autónoma de Yucatán, maella.gonzalez@correo.uady.mx;
[2] Facultad de Arquitectura y Diseño, Universidad de Colima, ggomez@ucol.mx

Abstract: There are no design standards which consider the climatic diversity of Mexico regarding the design of school buildings. At present, there are no thermal comfort studies in classroom environments of hot and humid climates in the country. A field study was conducted following the ASHRAE 55 methodology and adaptive comfort approach in three classrooms with natural ventilation (NV) and 2 with air conditioning (AC) in a scholar building from Merida, Yucatan. A total of 3,369 data sets from 255 students were collected for a six month period. The neutral temperatures obtained by linear regression were of 28.03°C in NV and 27.28°C in AC. A logistic regression analysis revealed preferred temperatures of 24.21°C in NV and 24.70°C in AC. The acceptable ranges obtained by thermal sensation analysis suggested ranges of 25.43°C to 30.62°C in NV and 23.01°C to 31.55°C in AC. It is necessary to conduct more thermal comfort surveys in schools in Mexico which address the association between thermal comfort and users' performance and health.

Keywords: thermal comfort, adaptive approach, naturally ventilated classrooms, air conditioned classrooms, pre-university students

1. Introduction

Thermal comfort studies in school buildings are important due to the associations found between thermal environment parameters, student performance and test results and health effects (Hoque & Weil, 2014, Auliciems, 1972, Mendell & Heath, 2005; Zeiler & Boxem, 2009). Consistently since 2006 the Programme for International Student Assessment (PISA) has ranked Mexico at the bottom of the list of countries belonging to the Organization for Economic Co-operation and Development (OECD) (INEE, 2016). If the thermal classroom environment is in any way responsible for these poor results it is essential that the government pay more attention to this topic.

In the hot sub humid regions of Mexico, thermal comfort studies have been carried out in low income dwellings (Garcia, 2009; Ruiz, 2011) but not in schools. Despite the climatic diversity of the country (Garcia & CONABIO, 1998), classroom thermal design parameters are the same for all Mexican regions. According to the National Institute for School Physical Infrastructure (INIFED) in 2011 (the organization in charge of educational infrastructure design and building temperature), the temperature in classrooms should be between 18°C and 25°C with a relative humidity of 50% and an air speed of 0-0.2m/s. However, the average thermal environment in naturally ventilated classrooms in Merida, Yucatan, falls outside this range, due to the fact that in May the temperature can reach 42°C with an average relative humidity of 78% (Comisión Nacional del Agua, 1994). This climate A(w) is present in 85.7% of Yucatan (INEGI, 2015).

1.1. Thermal comfort studies in tropical schools

Thermal comfort studies in schools have been done mainly in Hawaii (Kwok, 1998), in Japan's subtropical climate (Kwok & Chun, 2003), Singapore (Wong & Khoo, 2003), Taiwan (Hwang et al., 2006) and Malaysia (Puteh et al., 2012) but there are no reports of such studies in Mexican schools. The studies that exist invariably recorded acceptability ranges which surpassed the ones proposed by Standard 55 of the Thermal Environmental Conditions for Human Occupancy (ASHRAE 55), sometimes by as much as 10°C (Mishra & Ramgopal, 2013).

In Maceio, Brazil, Cândido et al. (2009) obtained an operative temperature of 28°C and Mishra & Ramgopal, in 2014, found that students felt comfortable in a range from 20 to 31°C. It was found that students adapted to climate better than projected by Fanger's theory (Alfano et al., 2013) in the predicted mean vote (PMV) and predicted percent dissatisfied (PPD) calculation, in which the model was obtained from laboratory experiments (Fanger, 1970).

1.2. Differences in the mode of ventilation

In the practical field, there have been differences found in the occupants' thermal environment perception between naturally ventilated buildings, air conditioned ones, and mixed spaces with both (Van Hoof, 2010). Occupants of air conditioned buildings are twice as sensitive to temperature changes as those without it (De Dear et al., 2014); in other words, they have greater difficulty in adapting to the thermal environment (Humprehys et al., 2016).

1.3. Objective

The purpose of this study is to define neutral, preferred temperatures, comfort ranges and temperature clouds in naturally ventilated (NV) and air conditioned (AC) mode classrooms in Yucatan´s hot, sub humid climate.

2. Research methodology

2.1. Study site

The field survey was conducted in Merida, Yucatan, Mexico. Merida (20°59'00" N, 89°38'00" W) is located at 9 m above sea level (INEGI, 2017) and has a hot sub humid climate. The climate is divided into three representative periods: hot dry, hot humid and cool, with transition periods (Canto, 2010). The average monthly temperatures lies between 27 and 31°C.

The school building (Figure 1.a) used for the study was chosen because it met the criteria of having both NV and AC mode areas (which is rare) and the classrooms were designed according to the most common model in the country, proposed by the Management Committee of the Federal School Building Program, currently known as INIFED (Table 1). The study was conducted in three NV mode classrooms and in two AC mode classrooms (Figures 1.b and 1.c).

It is difficult to find government schools in Merida with AC mode classrooms because of the operating cost of air conditioning. The public university in Merida that has air conditioning in some lecture rooms, has reported that 70% of its energy consumption is for thermal conditioning. Both NV mode and AC mode classrooms had ceiling fans. The air conditioners were of a window type.

2.2. Field investigation

The survey was carried out over 6 months in two climatic periods: hot dry (March to May) and hot humid (September to November). A total of 3,369 data sets were collected over 18 sessions from 8:00 to 18:30 between Tuesday and Thursday. Each group of students was visited twice and there were three data collection times in the morning shift and three in the afternoon shift.

The data collection sessions were during the first two weeks of the month, avoiding exam periods and other academic events. The questionnaire was delivered one hour after the students were seated to ensure a constant metabolic rate. The data was collected by the main author with the assistance of two mechatronics engineers (Figure 1.g).

2.3. Questionnaires and scales

The questionnaires were based on ISO 10551 (2011) and on ASHRAE 55 (2013); they were translated and revised, taking into consideration the thermal comfort questionnaires used in Mexico (Bojorquez, 2010; Martinez, 2011, Gomez Azpeitia & Martinez, 2012).

The questionnaire was divided into four sections: demographic data, thermal sensation, indoor air quality and health. Demographic information was the first to be collected; students were questioned about their gender, age, weight and height; they were asked to select a reason for choosing their seat, and were also questioned about the actions they took when they felt hot. The thermal sensation was measured on a 9 point scale, preference on a 7 point scale and acceptability with a binary scale, according to ISO 10551 (2011), (Table 2). 9 point scale was selected in order to evaluate the wide range of high temperatures in Yucatan´s hot dry and hot humid climates.

Table 1. Characteristics of surveyed classrooms

Parameters	Area (m^2)	Front orientation	Solar protection (North and south)	Window to wall ratios	Trees
NV mode classrooms					
Room 2	62.91	North-south	1.10m cantilever	50-50%	North-south
Room 4	62.91	North-south	1.10m cantilever	50-50%	North-south
Room 13	62.91	North-south	1.10m cantilever	50-50%	North
AC mode classrooms					
Room 25	62.91	North-south	1.10m cantilever	50-50%	North
Reading Workshop	87.21	North-south	1.10m cantilever	53-47%	North

Table 2. Thermal comfort scales

Scale value	Scale description		
	Thermal sensation	Thermal Preference	Thermal acceptability
-4	Very cold		
-3	Cold	Much cooler	
-2	Cool	Cooler	
-1	Slightly cool	Slightly cooler	
0	Neutral	Neither warmer nor cooler	Yes
1	Slightly warm	A little warmer	No
2	Warm	Warmer	
3	Hot	Much warmer	
4	Very Hot		

2.4. Physical measurements

Two weather stations were used, HD32.1 Deltha Ohm (Figure 1.f), calibrated and certified to measure the internal environment according to ISO 7730 (2005) and ISO 7726 (1998), (Table 3). Measurements were taken after stabilizing the equipment inside the rooms for 15 minutes. The stations were located in two thirds of the central corridor in the classroom and sensors were placed at a height of 0.6m above the floor.

The thermal environment parameters collected were: air temperature, globe temperature (15cm in diameter), mean radiant temperature, relative humidity, air speed and carbon dioxide. The data were collected at the same time participants filled out the thermal comfort questionnaire.

Table 3. Details of the instrument used for the environmental measurement

Description	Brand and model	Parameter	Sensitivity range	Uncertainty measure
Globe thermometer probe ø 150mm according to ISO 7243, ISO 7726. Sensor type Pt 100	TP3275 Delta Ohm	Globe temperature	-30°C…. +120°C	Class 1/3 DIN (±0.10°C)
Natural ventilation wet bulb probe. Sensor type Pt 100	HP3201 Delta Ohm	Wet bulb temperature, WBGT index	+4°C…. +80°C	Class A (±0.10°C)
Relative humidity and temperature combined probe. Sensors type: Thin film Pt 100 for temperature, capacity sensor for relative humidity	HP3207 Delta Ohm	Relative humidity, combined temperature	Temperature -30°C…. +100°C Relative humidity 5%RH÷98%RH	Temperature class 1/3 DIN (±0.10°C) Relative humidity ±2.5%
Omnidirectional hot wire probe NTC 10kohm	AP3203 Delta Ohm	Air speed	0.05÷5m/s	±0.02m/s (0.05÷1m/s) ±0.1 m/s (1÷5m/s)
Carbon dioxide probe	HD320B2	Carbon dioxide	0……5000ppm	±50ppm+3% of the measurement at 20°C, 50% RH and 1013hPa

3. Characteristics of subjects

The study subjects were pre-university students from 14 to 24 years old who had lived in the city of Merida for more than two years. The total number of participants was 255, 110 men and 115 women students. The average participants' age was 17 with a SD=1.59 and a sample size of (N)= 255. The sample was determined by the number of individuals who agreed to participate during recruitment and based on the climate seasons available for each study.

Students wore a uniform on a daily basis (Figure 1.d and Figure 1.e), the clothing insulation (clo) was calculated along with the metabolic rate (met) according to ASHRAE 55 (2013). Clothing insulation was calculated to be 0.50 clo and the metabolic rate was 1 met.

Figure 1.a: Survey environment in outdoor, Figure 1.b: Survey environment in NV, Figure 1.c: Survey environment in AC, Figure 1.d and 1.e: Typical uniforms, Figure 1.f: Climatic weather station HD32.1, Figure 1.g: Engineers assembling weather station

4. Results

4.1. Physical environmental measurements

The mean air temperature in the NV mode classrooms was 30.34°C and in the AC mode classrooms it was 28.52°C, the difference between these temperatures is 1.8°C, while the mean radiant temperatures in both types of ventilations show a difference of 0. 99°C (Table 4).

The operative temperature (T_{op}) was calculated with the formula proposed by ASHRAE 55 (2013):

$$T_{op}= AT_a+ (1-A)\ T_{mrt} \quad (1)$$

Where T_{op} is the operative temperature, T_a is the mean air temperature, T_{mrt} mean radiant temperature obtained directly from HD32.1 and A has values in relation to the air speed. It was selected according to the values < 0.2m/s, A= 0.5; from 0.2 to 0.6m/s, A= 0.6 and from 0.6 to 1.0m/s, A= 0.7.

During the study months, the mean outdoor temperature (T_{om}) was 29°C and was calculated according to the formula by Nicol et al., 2012:

$$T_{om} = (T_{omax} + T_{omin})/ 2 \quad (2)$$

Where T_{om} is the mean outdoor temperature, T_{omax} is the maximum mean daily outdoor temperature and T_{omin} is the minimum mean daily outdoor temperature.

Table 4. Environmental parameters for each type of ventilation

	Naturally ventilated				Air conditioned			
Environmental parameters	Mean	SD	Min	Max	Mean	SD	Min	Max
Air temperature (°C)	30.34	2.24	25.73	35.30	28.52	1.63	24.14	32.34
Mean radiant temperature (°C)	30.0	2.27	25.43	35.31	29.01	1.64	25.54	35.05
Globe temperature (°C)	30.16	2.25	25.61	35.29	28.77	1.52	24.99	32.15
Air velocity (m/s)	.25	0.13	.02	.71	.43	0.3	.02	1.29
Relative humidity (%)	57.99	11.64	33.12	80.25	51.26	6.24	30.61	72.63
Operative temperature (°C)	30.19	2.23	-	-	28.73	1.54	-	-
Monthly mean outdoor temperature (°C)	31	1.78	29	33	31	1.67	29	33

4.2. Characteristics of subjects

Of the total 255 participants, 21% reported that they slept in an air conditioned room, and 30% that they had classes in an AC mode classroom during the previous school term.

The adaptive actions that students commonly took to improve their thermal sensation included: opening windows (55%), turning the ceiling fan and the air conditioner on (78.5%), using a hand held fan (17%) and taking a soda or fresh beverage (50%).

4.3. Thermal sensation votes (TSV)

The survey included the question: *How do you feel at this precise moment?* I feel… which the subjects chose from the 9 point scale presented in Table 2. There was a higher frequency of thermal sensation votes between -1 and 1 in AC mode classrooms (Figure 2). The mean value of the thermal sensation votes in NV mode was found to be 0.80 (SD=.034) and .27 (SD=.310) in AC mode.

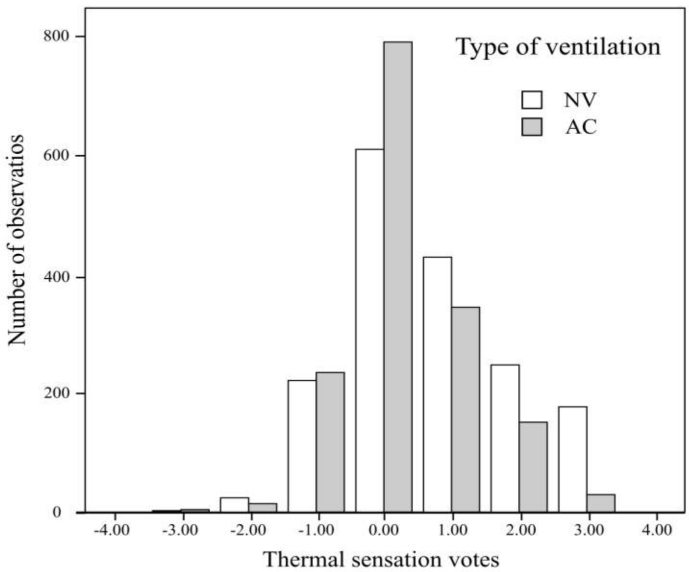


Figure 2. Distribution of thermal sensation votes in NV and AC mode

4.4. Thermal preference votes (TPV)

The survey contained the incomplete statement: *At this moment, you would prefer to feel…*, with a response from a 7 point scale that completed the statement. Students in both modes wanted to feel cooler; however, students in NV mode classrooms showed a higher preference to feel cooler (Figure 3). The mean vote in NV mode classrooms was found to be -1.55 (SD=.031), while in AC mode classrooms it was -1.36 (SD=.031).

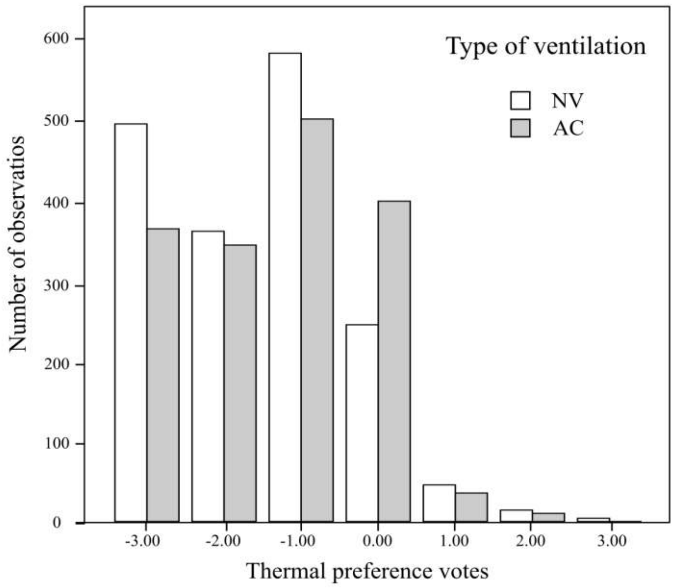


Figure 3. Distribution of thermal preference votes in NV and AC mode

4.5. Thermal acceptability votes (TAV)

The acceptability question used in the survey was: *Taking into account only your personal preference, would you accept this environment rather than reject it?* The response was a binary variable yes or no. In NV mode classrooms, 51.56% of participants reported accepted the thermal environment while 48.44% did not (*N*=1720). In AC rooms, 65.84% of the subjects considered the thermal environment acceptable and 37.16% unacceptable (*N*=1596) (Figure 4).

A Chi-square test reported significant differences in thermal acceptability votes for both ventilation modes ($\chi^2(1, N=3346)=48.89$; $p < .001$).

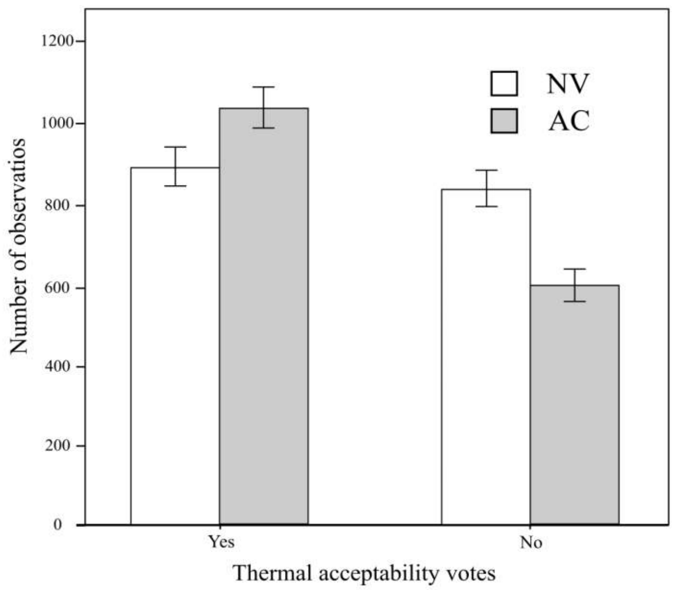


Figure 4. Distribution of thermal acceptability votes in NV and AC mode and 95% CI

4.6. Neutral temperature by linear regression and Griffith's comfort temperature

Neutral temperatures in NV mode and AC mode classrooms were obtained with a linear regression between the thermal sensation votes (TSV) and the operative temperature (T_{op}).

Natural ventilation:

TSV= 0.328_{Top} -9.194 (3)

(N=1727, r=.589, regression coefficient standard error (S.E.)=.011, p < .001, confidence intervals of 95%) (Figure 5).

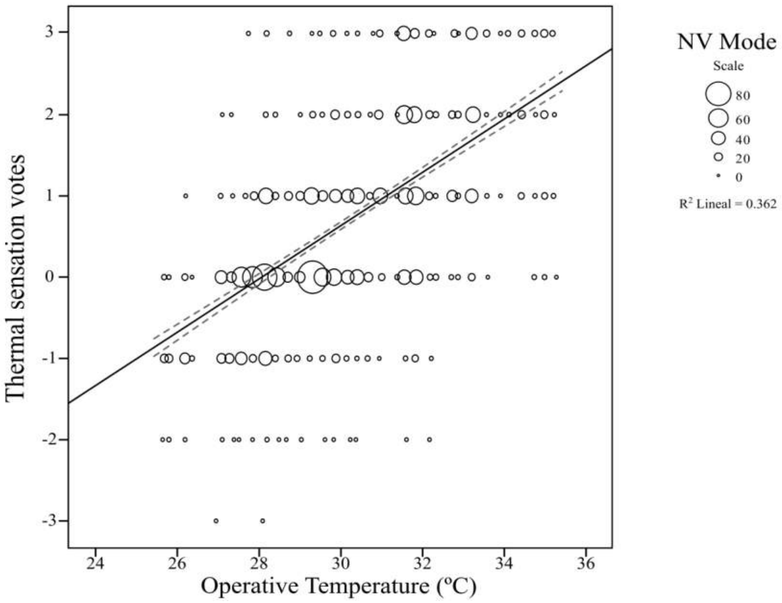


Figure 5. Linear regression of thermal sensation votes and operative temperature (T_{op}) in NV mode

Air conditioning:

TSV= 0.199_{Top} -5.430 (4)

(N=1642, r=.320, regression coefficient standard error (S.E.)=.015, p < .001, confidence intervals of l 95%) (Figure 6).

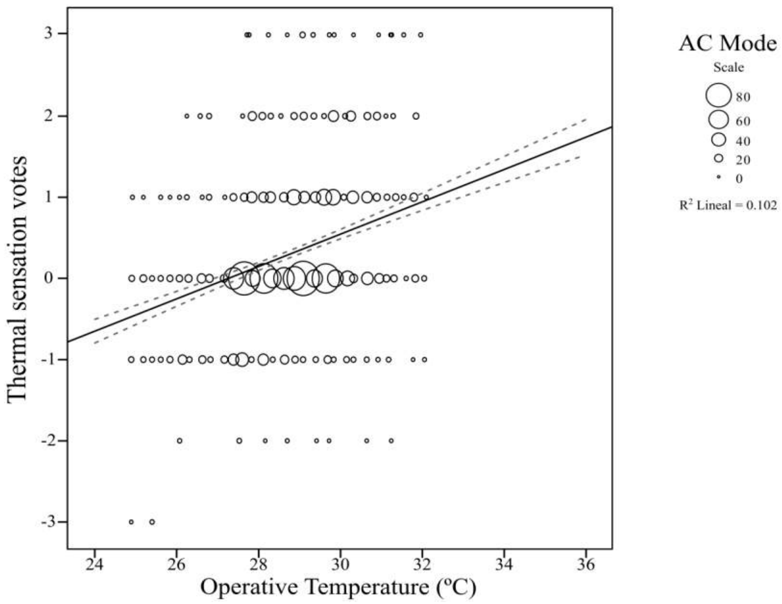


Figure 6. Linear regression of thermal sensation votes and operative temperature (T_{op}) in AC mode

Neutral temperatures were obtained by solving the equations: 28.03°C in NV mode classrooms and 27.28°C in AC mode ones. The thermal comfort range, calculated for 80% of acceptability, was from 25.43°C to 30.62°C in NV and from 30.01°C to 31.55°C in AC. Students' thermal sensitivity obtained by the regression coefficients 0.328 for NV mode and 0.199 for AC mode indicated that students adapted less to naturally ventilated than to air conditioned classrooms.

In order to compare the results, comfort temperatures were calculated for both ventilation modes by the Griffiths method with a $0.33K^{-1}$ slope proposed adaptive comfort studies (Griffiths, 1990), the comfort temperatures were of 28.11°C in NV and 27.85°C in AC rooms.

According to the calculator from the Center of the Built Environment (CBE) and to ASHRAE 55 (2013), 98.49% of thermal sensation votes for naturally ventilated areas fell out of the comfort zone, while 95% of votes for AC classrooms fell out of the comfort zone.

4.7. Adaptive model of thermal comfort

The dependence of the indoor temperature on the outdoor temperature is observed when we regressed T_{op} against *outdoor temperature taken at the actual hour of the survey interview* (T_o) that was used instead of the *mean monthly temperature* or *mean running temperature* because the correlation coefficient was higher than other metrics for T_o.

The outdoor temperature data were taken from meteorological tables provided by the Scientific Research Center of Yucatan, A.C. (CICY) weather station. We obtained a regression coefficient of 0.714 (r=.901, regression coefficient standard error (S.E.)=.008, $p < .001$) for NV mode and 0.248 (r=.473, regression coefficient standard error (S.E.)=.011, $p < .001$) for AC mode, (Figure 7).

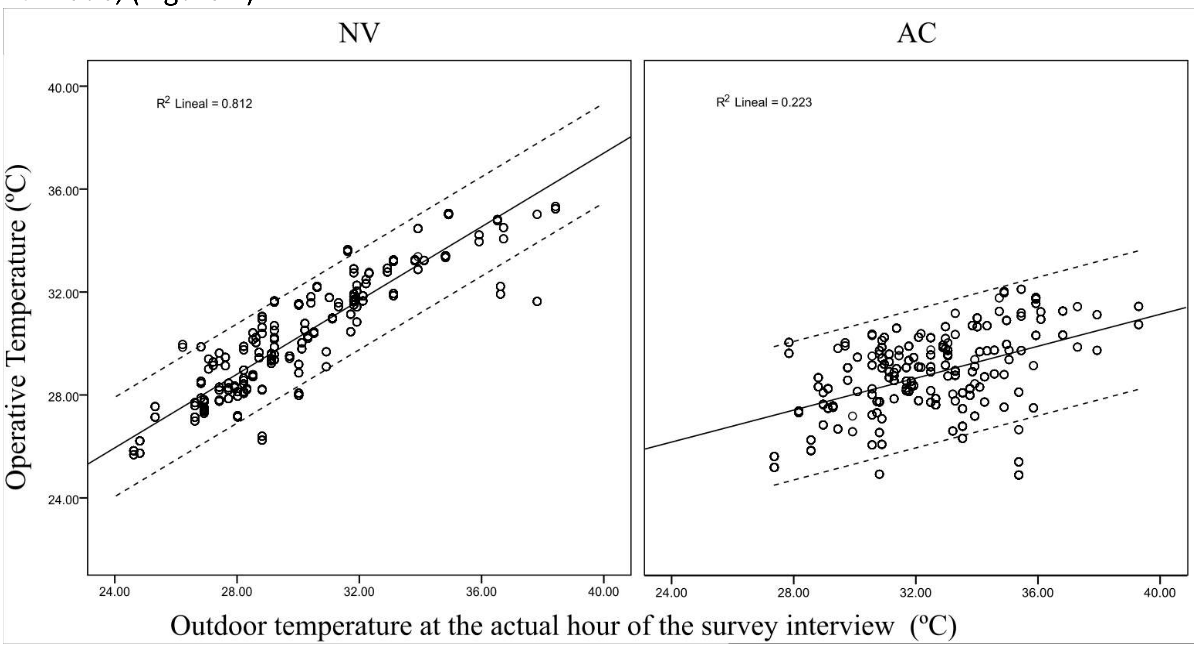


Figure 7. Temperature cloud for operative temperature (T_{op}) plotted against outdoor temperature taken at the actual hour of the survey interview (T_o) in NV and AC mode. Dotted lines indicate 95% CI of slope

In order to obtain the adaptive model equation we also regressed indoor neutral temperatures against outdoor temperature. This was done because the adaptive model of thermal comfort shows that indoor neutral temperatures are related to outdoor temperatures (Figure 8).

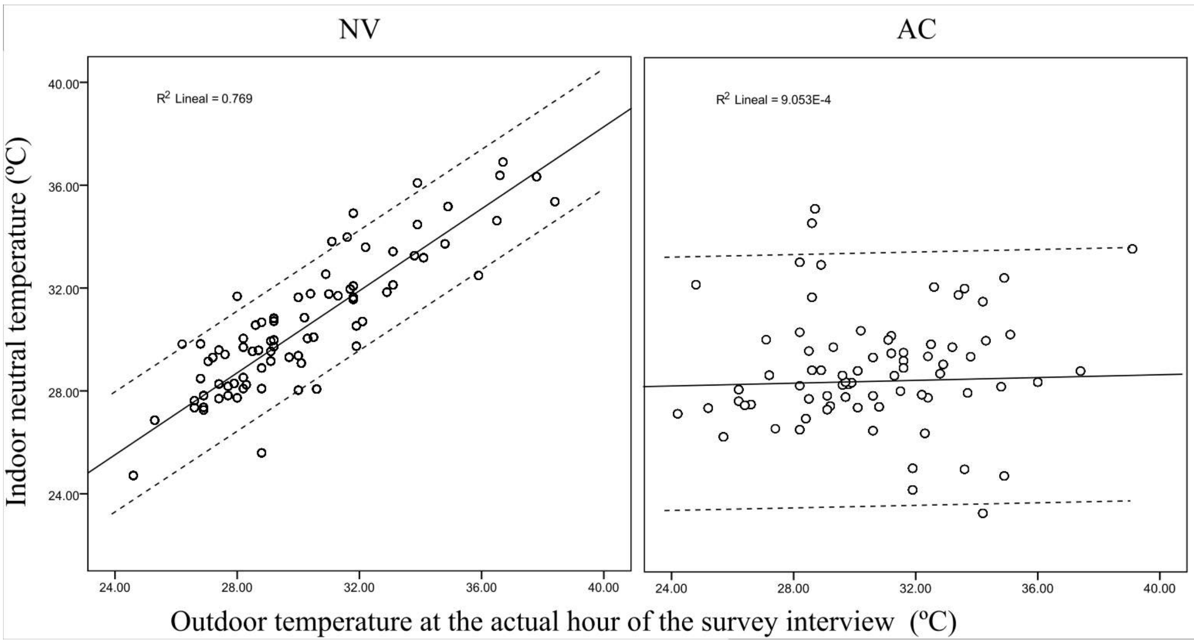


Figure 8. Plot of indoor neutral temperature in NV and AC mode against outdoor temperature taken at the actual hour of the survey (T_o). Dotted lines indicate 95% CI of slope

Natural ventilation model:

$$Tn=0.792\ T_o + 6.58 \quad (5)$$

(*N*=1653, r=.877, regression coefficient standard error (S.E.)=.011, p < .001)

Air conditioning model:

$$Tn=0.026\ T_o + 27.61 \quad (6)$$

(*N*=1546, r=.030, regression coefficient standard error (S.E.)=.022, p < .001)

In NV mode classrooms the adaptive model of thermal comfort shows a high dependency of indoor neutral temperatures on the outdoor temperatures taken at the actual hour of the survey while in AC mode classrooms that dependency was weak. Slopes in these equations are different from each other at 95% CI.

4.8. Preferred temperature by logistic regression

A logistic regression analysis revealed preferred temperatures of 24.21°C (n=1727, R^2=.032, regression coefficient standard error (S.E.)=.029, p < .01) in NV mode and 24.70°C (n=1642, R^2=.024, regression coefficient standard error (S.E.)=.036, p < .01) in AC mode. The preferred temperature for both types of ventilation (24.70°C) was calculated by the logistic regression model (Figure 9). The model explained 3.9% (Cox and Snell R^2) of the thermal preference variance and classified correctly 74.4% of cases. The odds ratio was 1.265, which indicates a very weak relationship.

The equation for both types of ventilation is:

$$\hat{p} = \frac{2.7183^{-5.809 + 0.235x}}{1+ 2.7183^{-5.809 + 0.235x}} = \frac{2.7183^{-5.809 + 0.235x(24.72)}}{1+ 2.7183^{-5.809 + 0.235x(24.72)}} = 0.5 = 50.00\% \quad (7)$$

(N=3357, R^2=.035, regression coefficient standard error (S.E.)=.021, p < .01)

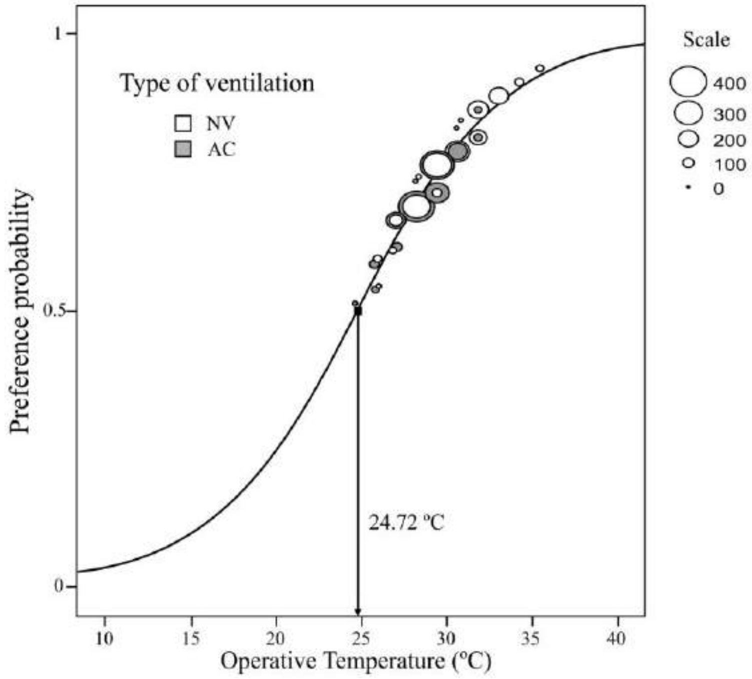


Figure 9. Logistic regression model for preferred temperature in NV and AC mode

4.9. Comparison between acceptability methods for the different types of ventilation

The three ways to determine acceptability are observed in Figure 10, where the thermal sensation votes scored higher percentages than direct acceptability. Thermal preference obtained the lowest scores.

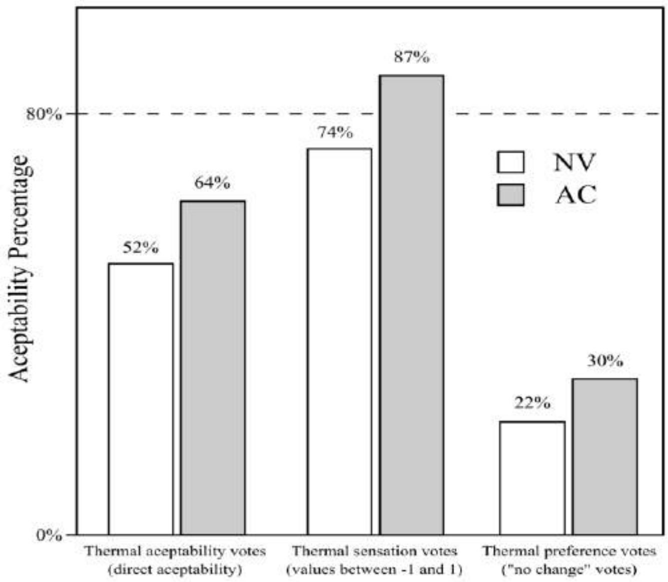


Figure 10. Comparison between acceptability methods for the different types of ventilation

The thermal acceptability and the thermal sensation votes overlapped in the contingency table (Table 5); the differences between the ventilation types in the acceptability band (1 and -1) differed in 6.5%. When the thermal acceptability and preference votes crossed, the thermal difference between both types was 12.3% (Table 6).

Table 5. Cross-tabulation thermal acceptability and thermal sensation scale

Thermal acceptability votes		Thermal sensation votes		
		-3, -2	-1, 0, 1	2, 3
Natural ventilation	Acceptable	20 (80.0%)	762 (61.0%)	91 (21.7%)
	Unacceptable	5 (20.0%)	487 (39.0%)	329 (78.3%)
Air conditioning	Acceptable	16 (88.9%)	909 (67.5%)	57 (32.0%)
	Unacceptable	2 (11.1%)	437 (32.5%)	121 (68.0%)

Table 6. Cross- tabulation thermal acceptability and thermal preference scale

Thermal acceptability votes		Thermal preference votes		
		Cooler	No change	Warmer
Natural ventilation	Acceptable	352 (41.9%)	528 (61.3%)	5 (35.7%)
	Unacceptable	489 (58.1%)	333 (38.7%)	9 (64.3%)
Air conditioning	Acceptable	348 (50.4%)	678 (73.6%)	4 (44.4%)
	Unacceptable	342 (49.6%)	243 (26.4%)	5 (55.6%)

5. Discussion

5.1. Comparison with previous studies

To analyze the thermal sensation votes, the 9 point scale was transformed to a 7 point one, according to the procedures by Humphreys et al., 2016.

The differences in the distribution patterns of thermal sensation votes in NV mode and AC mode classrooms were found to be larger in the present study than those reported by Hwang et al., 2009 in Taiwan and Indraganti et al., 2014 in Chennai and Hydebarad; the outdoor temperatures in this study were more similar to those of Chennai; however, that study was conducted in office rooms.

The neutral temperatures obtained by linear regression in both types of ventilation showed a difference of 0.75°C, since temperature in NV rooms was 28.03°C and in AC rooms, of 27.28°C. The difference in neutral temperatures for both types of ventilation agrees with the findings by Kwok (1998) in Hawaii and Hwang (2009) in Taiwan, with a difference of 0.6°C in both studies.

The calculated neutral temperatures are similar to those found by Nguyen in the Southeast of Asia (2012) who determined 27.9°C in natural ventilation and 25.8°C in air conditioning, however, they are more similar to the comfort temperatures obtained by Indraganti in the South of India (2014), 28°C in natural ventilation and 26.4°C air conditioning. The ranges obtained for 80% of acceptability were from 25.43 to 30.62°C in NV and from 23.01 to 31.55°C in AC, lower than those found by Mishra & Ramgopal in 2014.

5.2. Regression coefficients in naturally ventilated and air conditioned mode classrooms

In NV mode classrooms the regression coefficient was 0.328 and in AC mode was 0.199, which indicate less adaptation to NV rooms compared to AC ones. Zhang et al., 2013 and Humprheys et al. (2016), reported higher coefficients in AC mode compared to NV mode.

The clearly oriented preference towards fresher temperatures and the low direct acceptability of nearly 52% in NV mode classrooms could stem from low adaptability; however, the regression coefficient found in NV areas is similar to the regression coefficient obtained by Karyono (2000) in Jakarta offices, of 0.32 K^{-1}, as well as the one obtained by Indraganti (2010), of 0.31K^{-1}. The low coefficient found in AC mode could be explained by the small number of AC mode classrooms available, which are therefore in great demand. Another explanation could be that the students in AC always have the option of going outside if they begin to feel cold.

5.3. Temperature clouds in NV an AC mode

Neutral temperatures in NV mode relates to outdoor conditions. When indoor Tn plotted against T_o in AC mode there is a small positive correlation, probably because indoor temperature is decoupled from the outdoor temperature (Humpreys, et al. 2016), but in this case there is a larger temperature range.

6. Conclusions

The dynamics of classroom sessions and the layout in school buildings (indoor and outdoor space distribution) allow students in air conditioned rooms to experience the indoor and outdoor environments in an alternate way, which visibly improves their sensitivity and adaptive capacity, as shown by the regression coefficient of 0.199 found in the classrooms.

Given that the air conditioned classrooms had a higher air speed of up to 1.29m/s, averaging 0.35m/s and a constant relative humidity of about 50%, the acceptability range in these rooms was higher (8.54°C) than in the naturally ventilated ones.

The thermal environment conditions in NV mode classrooms do not comply with the recommendations by INIFED (2011), which is in charge of designing schools in Mexico; despite this, in the hot sub humid climate, students accept temperature ranges which go from 25.43 to 30.62°C in NV mode and from 23.01 to 31.55°C in AC mode which differs from those proposed by this institute: 18 to 25°C. A recommendation coming out of this study is that INIFED´s standards should be specific to each of Mexico´s climate types.

The students' acceptability ranges are larger than the calculated ones according to ASHRAE 55 (2013) in naturally ventilated and air conditioned classrooms.

The highest acceptability percentages were obtained with the thermal sensation votes and the lowest with the thermal preference votes; the participants in both types of ventilation preferred lower temperatures.

The present study found similar results to those presented by Hwang et al., 2006, who stated that at higher latitudes, the neutral temperature is lower; Merida has a lower latitude, therefore, the neutral temperature was higher than in locations at higher latitudes.

Temperature clouds show the high dependence of thermal comfort to outdoor temperature in NV mode and the partial independence in AC mode.

7. Aknowledgements

The present study was conducted thanks to the financial and logistic support of the National Council of Science and Technology (CONACYT), and Dr. Raul Canto Cetina, Head of the Bioclimatic Laboratory at the Facultad de Arquitectura, Universidad Autónoma de Yucatán.

8. References

Alfano, F., Ianniello, E. & Palella, B., 2013. PMV-PPD and acceptability in naturally ventilated schools. Building and environment. [online]. 67, 129-137. Available at: https://doi.org/10.1016/j.buildenv.2013.05.013 [Accessed 3 June 2017].

ASHRAE , 2013. *ASHRAE Standard 55-2013 (Thermal Environmental Conditions for Human Occupancy).* Atlanta, Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers .

Auliciems, A., 1972. Classroom performance as a function of thermal comfort. *International Journal of Biometeorology.* [online]. 16(3), 233-246. Available at: https://link.springer.com/article/10.1007/BF01553735 [Accessed 5 September 2017].

Bojórquez, G., 2010. *Confort Térmico en Exteriores: Actividades en Espacios recreativos, en clima cálido seco extremo.* PhD. Universidad de Colima.

Canto, R., 2010. *Determinación de las características arquitectónicas de la vivienda yucateca necesarias para lograr su adecuado funcionamiento térmico. Definiendo la vivienda sustentable.* México: Universidad Autónoma de Yucatán.

CONAGUA, 2017. *Información Climatológica por Estado.* [online] México: Comisión Nacional del Agua Available at: http://smn.cna.gob.mx/es/informacion-climatologica-ver-estado?estado=yuc [Accessed 30 December 2017].

De Dear, R., Kim, J., Cándido, C., Deuble, M., 2014. Summertime Thermal Comfort in Australian School Classroom. In: *Proceedings of 8th Windsor Conference: Counting the cost of comfort in a changing world* [online] Windsor, UK, 10 - 13 April 2014. London: Network for Comfort and Energy Use in Buildings, 271-291. Available at: http://nceub.org.uk/W2014/webpage/W2014_index.html. [Accessed 29 December 2017].

Diario Oficial de la Federación, 2014. *Programa Institucional del Instituto Nacional de Infraestructura Física, Educativa, 2014-2018.* [online] Ciudad de México: México. Secretaría de Gobernación. Available at: http://www.dof.gob.mx/nota_detalle.php?codigo=5343877&fecha=08/05/2014 [Accessed 29 December 2017].

Cândido, C., de Dear, R., Lamberts, R., Bittencourt, L., 2009. Air movement preference and Thermal Comfort. A survey in classrooms during summer season in Brazil. In: *Architecture, Energy and the Occupants's Perspective Proceedings of 26th Conference on Passive and Low Energy Architecture.* [online] Quebec city, Canada, 22 - 24 de june 2009. Quebec: Les Presses de l'Université Laval, 522-526. Available at: http://www.plea2009.arc.ulaval.ca/En/Proceedings.html. [Accessed 29 December 2017].

Fanger, P., 1970. *Thermal comfort: analysis and applications in environmental engineering*. New York: McGraw-Hill.

Gómez-Azpeitia, G., Martínez, K., 2012. Thermal Comfort and Health conditions in air conditioned offices in a Warm and Sub-humid Climate. In: *28th Conference*, *Opportunities, Limits & Needs towards an environmentally responsible architecture.* [online] Lima, Perú: 7-9 November 2012. Available at: http://plea-arch.org/ARCHIVE/2012/files/T02-20120130-0075.pdf [Accessed 29 December 2017].

García, C. (2009). *La Toma de Decisiones y el Confort Térmico en la Vivienda Autoproducida en Mérida, Yucatán.* PhD. Universidad de Colima.

García,E. & CONABIO, 1998. *Catálogo de metadatos geográficos.* [Online] Mexico: Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. Available at: http://www.conabio.gob.mx/informacion/metadata/gis/clima1mgw.xml?_xsl=/db/metadata/xsl/fgdc_html.xsl&_indent=no [Accessed 30 December 2017].

Gómez- Azpeitia, G., Ruiz, P., 2007. *Determinación de la amplitud del rango de confort térmico preferente para las personas que habitan en clima tropical sub-húmedo.* Reporte técnico final CGIC-400/06-A-000, FRABA. Ciudad de Colima:Universidad de Colima, México.

Griffits, I., 1990. *Thermal comfort studies in buildings with passive solar features, field studies.* Report of the Commission of the European Community. UK. ENS35 090; 1990.

Hoque, S., Weil, B., 2014. Cold comfort: Thermal satisfaction in academia. In: *Proceedings of 8th Windsor Conference: Counting the cost of comfort in a changing world.* [online] Windsor, UK, 10 - 13 April 2014. London: Network for Comfort and Energy Use in Buildings, 292-301. Available at: http://nceub.org.uk/W2014/webpage/W2014_index.html. [Accessed 29 December 2017].

Humpreys, M., Nicol, F,. Roaf, S., 2016. *Adaptive Thermal Comfort: Foundations and Analysis.* U.K.: Routledge.

Hwang, R, Lin, T & Kuo, N., 2006. Field experiments on thermal comfort in campus classrooms in Taiwan. *Building and Environment.* [online]. 38(1), 53-62. . Available at: https://www.deepdyve.com/lp/elsevier/field-experiments-on-thermal-comfort-in-campus-classrooms-in-taiwan-6UBJbl92Vg [Accessed 21 September 2017].

Hwang et al., 2009. Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan. *Int j Biometeorol.* [online]. 53(2), 189-200. Available at: https://www.ncbi.nlm.nih.gov/pubmed/19132409 [Accessed 15 March 2017].

Indraganti, M., 2010. Thermal comfort in naturally ventilated apartments in summer: findings from a field study in Hyderabad, India. *Applied Energy.* [online]. 87(3), 866-883. Available at:

https://doi.org/10.1016/j.apenergy.2009.08.042 [Accessed 7 April 2017].

Indraganti, et al., 2014. Adaptive model of thermal comfort for offices in hot and humid climates of India. *Building and environment.* [online]. 74, 39-53. Available at: https://doi.org/10.1016/j.buildenv.2014.01.002 [Accessed 7 April 2017].

INEE, 2016. *México en PISA 2015.* 1a edición. México: Instituto Nacional para la Evaluación de la Educación. Available at: http://www.inee.edu.mx/images/stories/2016/PISA2016/noviembre/PISA_2015-informe.pdf [Accessed 29 December 2017].

INEGI, 2015, *Conociendo Yucatán - Quinta Edición.* México: [online]. p-9. Available at: http://internet.contenidos.inegi.org.mx/contenidos/productos//prod_serv/contenidos/espanol/bvinegi/productos/estudios/conociendo/702825213237.pdf [Accessed 29 December 2017].

INEGI, 2016, *Anuario estadístico y geográfico de Yucatán 2016.* México: [online]. Available at: http://www.datatur.sectur.gob.mx/ITxEF_Docs/YUC_ANUARIO_PDF16.pdf [Accessed 29 December 2017].

INIFED, 2011. *Normas y especificaciones, estudios, proyectos, construcción e instalaciones.* vol. 3, no. I. [online] México: Instituto Nacional de Infraestructura Física Educativa. Available at: http://www.inifed.gob.mx/doc/normateca/tec/V3-HF/Volumen_3_Tomo_I_Diseno_Arquitectonico.pdf [Accessed 18 May 2017].

ISO 10551, 2011. *Ergonomics of the thermal environment – assessment of the influence of the thermal environment using subjective judgement scales.* Geneva, Switzerland: International Organization for Standardization.

ISO 7730, 2005. *Ergonomics of the thermal environment- analytical determination and determination and interpretation of the thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.* Geneva, Switzerland: International Organization for Standardization.

ISO 7726, 1998. *Ergonomics of the thermal environment- Instruments for measuring physical quantities.* Geneva, Switzerland: International Organization for Standardization.

Karyono, T.,2000. Report on thermal comfort and building energy studies in Jakarta. *Building and Environment.* 35, pp. 77-90.

Kwok, A., 1998. *Thermal Comfort in Naturally-Ventilated and Air-Conditioned classrooms in the Tropics*. PhD. University of California at Berkeley.

Kwok, A & Chun, C., 2003. Thermal comfort in Japanese schools. *Solar Energy.* [online]. 74(3), 245-252. Available at: https://doi.org/10.1016/S0038-092X(03)00147-6 [Accessed 12 April 2017].

Martínez, T., 2011. *Temperatura y rango de confort térmico en oficinas climatizadas artificialmente en clima cálido subhúmedo.* M.Arch. Coquimatlán, Colima, México: Universidad de Colima.

Mendell, M.J & Heath, G.A, 2005.Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. *Indoor Air.*[online]. 15(1), 27-52. Available at: https://www.ncbi.nlm.nih.gov/pubmed/15660567 [Accessed 12 April 2017].

Mishra, A & Ramgopal, M., 2013. Field Studies in Thermal Comfort- An overview. *Building and Environment.*[online]. 64, 94-106. Available at: https://doi.org/10.1016/j.buildenv.2013.02.015 [Accessed 11 April 2017].

Mishra, A & Ramgopal, M., 2014. Thermal comfort in undergraduate laboratories- A field study in Karaghpur, India. *Building and Environment.* [online]. 71(2), 223-232. Available at: https://doi.org/10.1016/j.buildenv.2013.10.006 [Accessed 11 April 2017].

Nicol, F., 2017. *Temperature and adaptive comfort in heated, cooled and free-running dwelings. Building Reseacrh & Information.*[Online]. 45(7), 730-744. Available from: https://dx.doi.org/10.1080/09613218.2017.1283922 [Accessed 27 november 2017].

Nicol, F., Humphreys, M. and Roaf, S., 2012. *Adaptive thermal comfort:principles and practice.* London: Routledge.

Nguyen, A, Kumar, M & Reiter, S., 2012. An adaptive thermal comfort model for hot humid South-East Asia. *Building and Environment.* [online]. 56(2), 291-300. Available at: https://doi.org/10.1016/j.buildenv.2012.03.021 [Accessed 21 April 2017].

Puteh et al., 2012. Thermal Comfort in Classroom: Constraints and Issues. *Procedia - Social and Behavioral Sciences.* [online]. 46, 1834-1838. Available at: https://doi.org/10.1016/j.sbspro.2012.05.388 [Accessed 29 March 2017].

Rijal, HB., Yoshida, H., 2005. Winter Thermal Comfort of Residents in a Himalayan Region of Nepal. In: *Summaries of Technical Papers of Annual Meeting AIJ.* AIJ, D-2, 473-474.

Ruiz, P., 2011. *Confort Térmico variable en clima cálido subhúmedo.* PhD. Universidad de Colima.

Van hoof, J., 2008. Forty years of Fanger's model of thermal comfort: comfort for all?. *Indoor Air.* [online]. 18(3), 182-201. Available at: https://www.ncbi.nlm.nih.gov/pubmed/18363685 [Accessed 14 May 2016].

Wong, N & Khoo, S., 2003. Thermal comfort in classrooms in the tropics. *Energy and Buildings.* 35(4), pp. 337-351.

Zeiler, W & Boxem, G., 2009. Ventilation of Sustainable Schools: Better than Traditional Schools?. *ASHRAE Transactions.* [online]. 115(2), 1-9. Available at: https://www.researchgate.net/publication/288482920_Ventilation_of_sustainable_schools_Better_than_traditional_schools [Accessed 18 December 2014].

Zhang, Y, Chen, H & Meng, Q., 2013. Thermal comfort in buildings with split air-conditioners in hot-humid area of China. *Building and Environment.* [online]. 64(2), 213-224. Available at: https://doi.org/10.1016/j.buildenv.2012.09.009 [Accessed 22 January 2017].

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

What the Indoor Air Temperatures in Houses in Three Australian Cities Tell Us

Dong Chen[1]*, Zhengen Ren[1], Melissa James[1]

[1] CSIRO Land and Water, Private Bag 10, Clayton South 3169, Australia
*Corresponding email: Dong.Chen@CSIRO.au

Abstract: This study analysed over 1.8 million measurements of air conditioner power consumption and indoor/outdoor air temperatures in 129 houses in Adelaide, Brisbane and Melbourne from 2012 to 2014. It was found that the preferred indoor air temperature range, at which occupants are most unlikely to operate air conditioners, increases for warmer local climates. In each city, the air conditioner switch on and off indoor temperatures, and the indoor temperatures when air conditioner is in operation can be grouped into three prevailing outdoor temperature ranges: the low range, the shoulder range and the high range. Occupants are not very tolerant at the low and high temperature ranges, while they are more adaptive with the shoulder temperature range. This finding supports the simplified static thermostat setting approach used in the *AccuRate* software for house energy rating, though the existing thermostat settings should be adjusted with more research in understanding thermal comfort and air conditioner operation behaviours in residential houses.

Keywords: thermal comfort; thermostat settings; triggering temperature; residential buildings

1. Introduction

In recent years, energy consumption in the residential sector, which accounts for 11% of Australian total energy consumption, has been relatively flat or in decline (DOEE, 2017). This has been partially attributed to the adoption of more energy efficient housing (DOEE, 2017). Since 1993, Australian state and territory governments and building regulators gradually introduced the Nationwide House Energy Rating Scheme (NatHERS) in order to improve the energy efficiency of residential buildings. In supporting the scheme, a dynamic building simulation software *AccuRate* is used for NatHERS star rating for houses to demonstrate compliance with Australian building code energy efficiency requirements.

The *AccuRate* software was developed by coupling a frequency response building thermal model and a multi-zone ventilation model for energy requirement calculation of residential buildings (Walsh & Delsante, 1983; Ren & Chen, 2010; Delsante, 2005). Taking into account the local climate and building fabrics, *AccuRate* automatically switches the building operation between mechanical air conditioning and natural ventilation operation when natural ventilation satisfies occupant thermal comfort and calculates hourly heating and cooling energy requirement over a period of one year. Then, *AccuRate* assigns the house a NatHERS star rating based on the calculated heating and cooling energy requirement.

For the calculation of building heating and cooling energy requirement, the thermostat settings are commonly set according to standards such as ASHRAE 55-2013 (ASHRAE, 2013) for achieving the required occupant thermal comfort indoor environment. The heating and cooling thermostat settings used in *AccuRate* are specified in the Protocol for House Energy Rating Software (ABCB, 2006). For living spaces, a heating thermostat setting of 20°C is used. For sleeping spaces, a heating thermostat setting of 18°C from 7:00 to 9:00 and 16:00 to 24:00, and 15°C from 24:00 to 7:00. The cooling thermostat is set equal to the neutral temperature of January (the middle month of the summer in the southern hemisphere) for the corresponding climate zone. It is also assumed that cooling is triggered when indoor air temperature is 2.5°C above the neutral temperature which corresponds to 90% acceptability of the ASHRAE adaptive thermal comfort model (de Dear & Brager, 1998; ASHRAE, 2013). The cooling thermostat settings, although not exactly corresponding to the ASHRAE adaptive comfort model (ASHRAE, 2013), are based on the understanding that acceptable thermal conditions vary with the local climates.

The thermostat settings can significantly affect the calculation of the heating and cooling energy requirement and thus impact on whether or not a house design obtains building approval. James et al (1996) simulated a typical house in three Florida cities and showed that cooling energy can be reduced over 20% per °C increase in the thermostat temperature. Manning et al (2007) evaluated experimentally a pair of identical twin houses at the Canadian Centre for Housing Technology and showed that cooling energy reduction can be over 10% per °C increase in the thermostat temperature. Recently, using *AccuRate* simulations, Ren & Chen (2017) demonstrated that relaxing the cooling triggering temperature from 2.5°C to 3.5°C above the neutral temperature (corresponding to 80% acceptability of the ASHRAE adaptive comfort model) reduces 40% of the calculated space cooling energy requirement in regions with a hot summer climate and wide diurnal temperature swing (e.g. Alice Springs) for a heavyweight double brick cavity construction house. For a high set lightweight weatherboard house, such a relaxing in the cooling triggering temperature can result in 25% reduction in the cooling energy requirement and a 2 star increase in tropical regions (e.g. Darwin). Large reductions over 95% in heating and cooling energy requirements were also reported by Shiel et al (2017) using *AccuRate* simulations for a house in Adelaide by relaxing both the heating and cooling triggering temperatures and the thermostat temperatures.

It is clear that both the triggering and thermostat set point temperatures used in *AccuRate* can have different, yet sometimes significant, impact on the calculated heating and cooling requirement for different house construction types in different climates. For example, by extending the cooling triggering temperature from 2.5°C to 3.5°C above the neutral temperature, light weight constructions become easier to pass the building energy efficient regulation requirements in tropical regions in comparison with heavyweight constructions (Ren & Chen, 2017). On the other hand, by decreasing the heating thermostat set temperature, heavyweight construction houses become easier to pass the regulation requirements in certain climates (Beckett et al, 2017). Consequently, the triggering temperature and thermostat set point temperature in *AccuRate* play important roles in construction types of the residential building sector in Australia. However, so far, it is still a question as to how well these thermostat settings reflect the thermal comfort and the real heating and cooling operations in Australian houses.

The existing ASHRAE adaptive thermal comfort model defines acceptable indoor conditions for free run buildings when vote casts are within the three central categories of comfort scale (slightly cool, neutral or slightly warm). For common naturally ventilated building designs, the ASHRAE standard specifies that the allowable indoor operative temperature shall be determined using the 80% acceptability limits. The ASHRAE adaptive thermal comfort model was established based on empirical data mainly from office buildings (de Dear, 1998) whose occupants are relatively restricted in their adaptive measures and perceived control of the environment in comparison with those in residential buildings.

Direct application of the ASHRAE adaptive model to residential buildings has been questioned by previous studies (Peters et al, 2009; Lomas and Kane, 2013; Daniel, 2015; Kim et al, 2016; Alshaikh & Roaf, 2016; Nicol, 2017). Nicol (2017) examined the records from different research groups on indoor temperatures and comfort in residential buildings in Japan, England, Saudi Arabia, Russia, China, Australia, Belgium, Denmark, Portugal and New Zealand. A common finding of these studies is that in residential houses, whether heated, cooled or free running (FR), the comfort temperature range is generally wider than the corresponding range in ASHRAE standard due to residential occupants' wider adaptive options, perceived control etc. However, the width of the comfort temperature range and the slope for the regression line between the neutral temperature and the prevailing mean outdoor air temperature are not consistent among studies. An indoor operative temperature range from 7 to 14°C was reported by different researchers (Kim et al, 2016; Nicol, 2017). For the regression line between the neutral temperature and the prevailing mean outdoor air temperature, some reported a steep slope of around 0.5, 0.6 (Daniel, 2015; Nicol, 2017). Some gave a slope of below 0.3 (Kim et al, 2016) and even below 0.1 (Alshaikh & Roaf, 2016).

In summary, so far, studies on thermal comfort and heating and cooling operation in residential buildings are insufficient to form credible methodology for determining the adequate thermostat settings for energy efficient building designs and energy ratings. More research is needed. The current study aims at adding to the understanding of the indoor temperatures in heated and cooled Australian houses through analysing measurements of air conditioner (A/C) power consumption and indoor/outdoor air temperatures in 129 houses in Adelaide, Brisbane and Melbourne from 2012 to 2014.

2. Data collections

To investigate the impact of the NatHERS house energy efficiency regulation on Australian residential buildings, the Australian Government commissioned CSIRO to do a survey and monitoring study in Brisbane, Adelaide and Melbourne in 2012. These three cities have different climates: Brisbane (warm humid summer, mild winter), Adelaide (warm temperate) and Melbourne (mild temperate) respectively. Half-hour electricity consumption data was collected using direct monitoring of electricity at the switchboard for 64, 66 and 59 houses in Brisbane, Adelaide and Melbourne respectively for 9 months from the beginning of June 2012 to the end of February 2013. The monitoring was continued after February 2013 to allow follow-up studies. Temperature measurements at the living areas were also taken at 30 minute intervals using Thermochron temperature sensor/data logger which has an accuracy of ±1°C within the temperature range from -30 °C to +70 °C. The temperature sensors were installed at locations where direct sunlight was avoided.

All the houses were built between 2001 and 2011. Among these monitored houses, 129 houses (21 in Melbourne, 49 in Adelaide and 59 in Brisbane), which have at least one reverse cycle air conditioner installed, were chosen for this study, because these 129 houses have dedicated electric circuits for air conditioners. Between June 2012 and August 2014, a total of 1.86 million sets of half hour measurements were collected on A/C electricity consumption and living room air temperature for the 129 houses. The majority of these measurements were taken between the beginning of June 2012 to the end of February 2013. For each house, the air temperatures of the nearest Bureau of Meteorology (BoM) weather station were obtained as the outdoor air temperature. For details of the monitoring methodology, please refer to Ambrose et al (2013).

3. Results and discussions

The A/C power consumption measurements were analysed to find the A/C switch on and switch off time. A/C switch on is determined by a power consumption jump from zero or a low standby power consumption, while A/C switch off is judged by a power consumption drop to zero or a low standby power consumption. The indoor temperature at the beginning of the power jump is taken as the A/C switch on indoor temperature, $T_{switchon}$. Similarly, the A/C switch off indoor temperature, T_{off} was taken at the beginning of a power consumption drop. The indoor temperatures between the A/C switch on and switch off is the indoor temperature when A/C is in operation, i.e., $T_{operation}$.

3.1. A/C operation hours

Figure 1 shows the probability of using A/C in each hour of the day through the whole monitoring period for the three cities. It is seen that occupants are more likely to use A/C from 5pm to 10pm, less in the morning and lowest probability of using A/C during the sleeping hours from 11pm to 6 am. This trend is more obvious in Adelaide which has the highest probability of using A/C, followed by Melbourne. Brisbane has the lowest probability of A/C usage. The high occupancy rate during the late afternoon and evening hours is believed to contribute to this pattern of A/C usage.

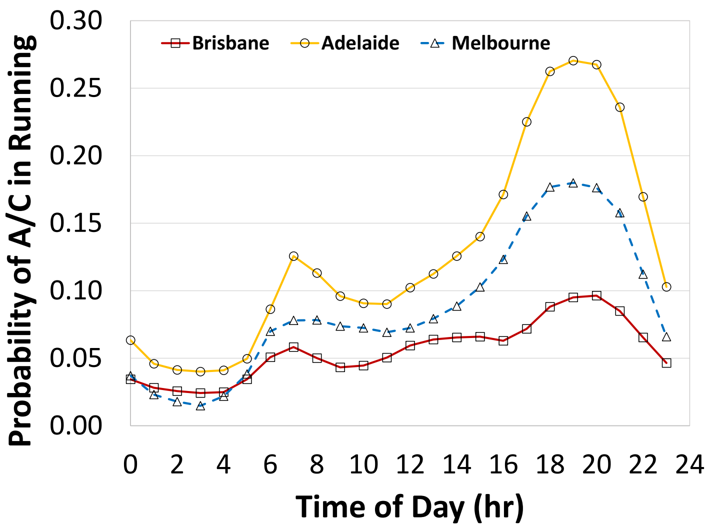


Figure 1. A/C “in running” probability at different time of the day in Brisbane, Adelaide and Melbourne

Figure 2 shows the outdoor air temperature distributions for the period from June 2012 to February 2013 for Brisbane, Adelaide and Melbourne. The relatively mild weather explains the lowest A/C usage in Brisbane. Figure 3 shows the probability distributions for different indoor temperatures in the 49 houses in Adelaide at different hours of the day. As expected, due to the diurnal outdoor temperature and solar radiation changes, many low indoor temperatures occur during sleeping hours, while most high indoor temperatures occur from the late afternoon to the early evening. Consequently, the high summer temperature in Adelaide results in the high probability of A/C operation in the late afternoon and evening which coincide with high house occupancy rate. The low A/C usage during sleeping hours seen in Figure 1 is believed due to the fact that sleeping in a cold indoor environment is relatively acceptable in comparison with sleeping in a hot indoor environment.

Although in average, the winter temperature in Melbourne is lower than that in Adelaide and Brisbane (refer to Figure 2), A/C is not normally used for space heating in

Melbourne. 15 out of the 21 houses in Melbourne were mainly heated by gas heaters, while 54 out of the 59 houses in Brisbane and 45 out of the 49 houses in Adelaide used A/C for space heating. This explains that the probability of A/C operation in Melbourne houses are lower than that in Adelaide during the sleeping hours from 11pm to 6 am.

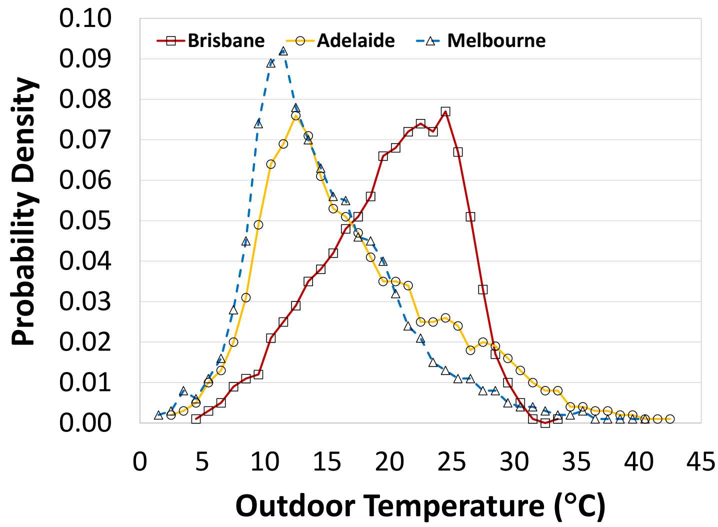


Figure 2. Outdoor temperature distribution from June 2012 to February 2013 for three cities

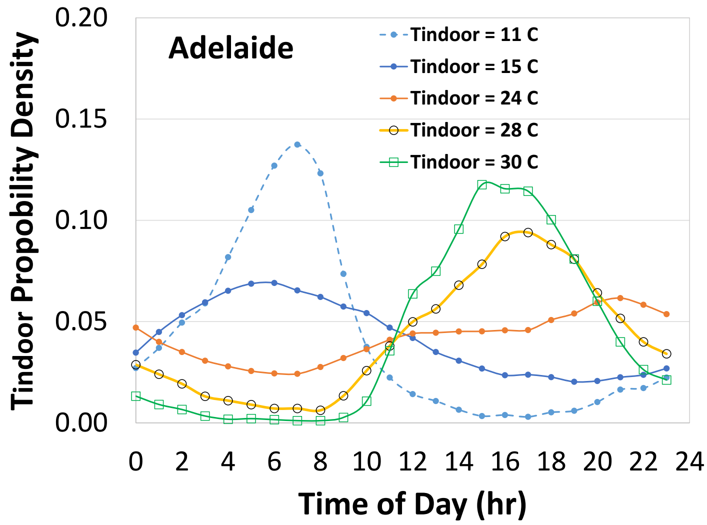


Figure 3. Indoor temperature distribution at different time of the day in all the houses in Adelaide

3.2. A/C switch on temperatures

When A/C is switched on, it means that the occupants would like to change the current indoor thermal condition which is most likely unsatisfactory. Figure 4 shows the probability of A/C switch on when the houses are at different indoor air temperatures. This probability is the number of A/C switch on at one specified indoor temperature divided by the total number of half hour records when the house is at this same indoor temperature. Figure 4 does not include the lowest and highest indoor temperatures experienced in the houses in each city, because switch on events for these extreme indoor temperatures are too low (less than 10). It is seen that A/C is most unlikely to be switched on at around 20-22.5°C, 21.5-24°C and 23.5-

26°C indoor temperatures in Melbourne, Adelaide and Brisbane. These temperature range around 20°C to 26°C is arguably the most preferred temperature range or the easiest temperature range for thermal adaption by the majority of the populations in buildings with heating and cooling (de Dear et al, 1997). These preferred temperature ranges increase with the average outdoor temperatures, which suggests thermal adaptation to the local climate.

Since many low indoor temperatures occur during sleeping hours (refer to Figure 3), this period has the lowest probability of A/C operation. This may explain that the switch on curve at low indoor temperatures in Figure 4 is not as decisive as the curve at high indoor temperatures which often occur during late afternoon and evening when occupants are awake and active. The probability of A/C switch on increases rapidly at high indoor temperatures above the preferred temperature ranges.

It is noted that the 80% and 90% acceptability limits of the ASHRAE adaptive thermal comfort model are set at 2.5°C and 3.5°C apart from the neutral temperature. It implies that statistically, the dissatisfactory rate increases approximately 100% for each °C increase in the difference between the indoor temperature and the neutral temperature at least for the temperature difference range between 2.5 and 3.5°C. In other words, statistically, the probability of A/C switch on is likely to increase rapidly with the increase in this temperature difference.

Figure 5 again shows the probability of A/C switch on when the houses is at different indoor air temperatures for the three cities respectively. However, in Figure 5, each curve is at a fixed running average outdoor temperature $T_{\text{runningaverage}}$, which is the mean temperature for the previous seven days. Due to small number of data points, the plots are scattered. The neutral temperatures calculated based on the ASHRAE adaptive thermal comfort model, i.e., Eq. (1), are also included for references.

$$T_{neutral} = 17.8 + 0.31T_{runningaverage} \qquad (1)$$

At low $T_{\text{runningaverage}}$, heating is the main function for the A/C operation. When $T_{\text{runningaverage}}$ is high, cooling is the main function for the A/C operation. The trend for heating is difficult to see perhaps again due to the fact that many low indoor temperatures occur during sleeping hours. For cooling, Figure 5 fails to show the trend that the probability of A/C switch on increases rapidly with an increase in the difference between the indoor temperature and the neutral temperature. For example, in Adelaide, there is no significant difference in the probability of A/C switch on for an indoor temperature at 28°C when $T_{\text{runningaverage}}$ is at 20°C, 23°C and 26°C which correspond to the temperature differences of 4.0°C, 3.1°C and 2.1°C. In Brisbane, the same can be found for an indoor temperature at 29°C when $T_{\text{runningaverage}}$ is at 23°C and 26°C which correspond to the temperature differences of 4.1°C and 3.1°C. Similar trends can be observed in Melbourne when $T_{\text{runningaverage}}$ is at 20°C and 23°C for the indoor temperatures from 25°C and 30°C. It is understood that the neutral temperatures calculated using Eq. (1) may be not suitable for residential houses (Nicole, 2017; Kim et al, 2016). Although there are around 4000 A/C switch on events in Melbourne, 15000 in Adelaide and 8000 in Brisbane, when divided into around 25 T_{switchon} and around 15-25 $T_{\text{runningaverage}}$ bins, the number of measurements for the data points in Figure 5 can still be limited. Nevertheless, these results suggests that the switch on of A/C is not a strong function of $T_{\text{runningaverage}}$ for cooling. In fact, for cooling, Figure 5 shows that the probability of A/C switch on is more related to the indoor temperature.

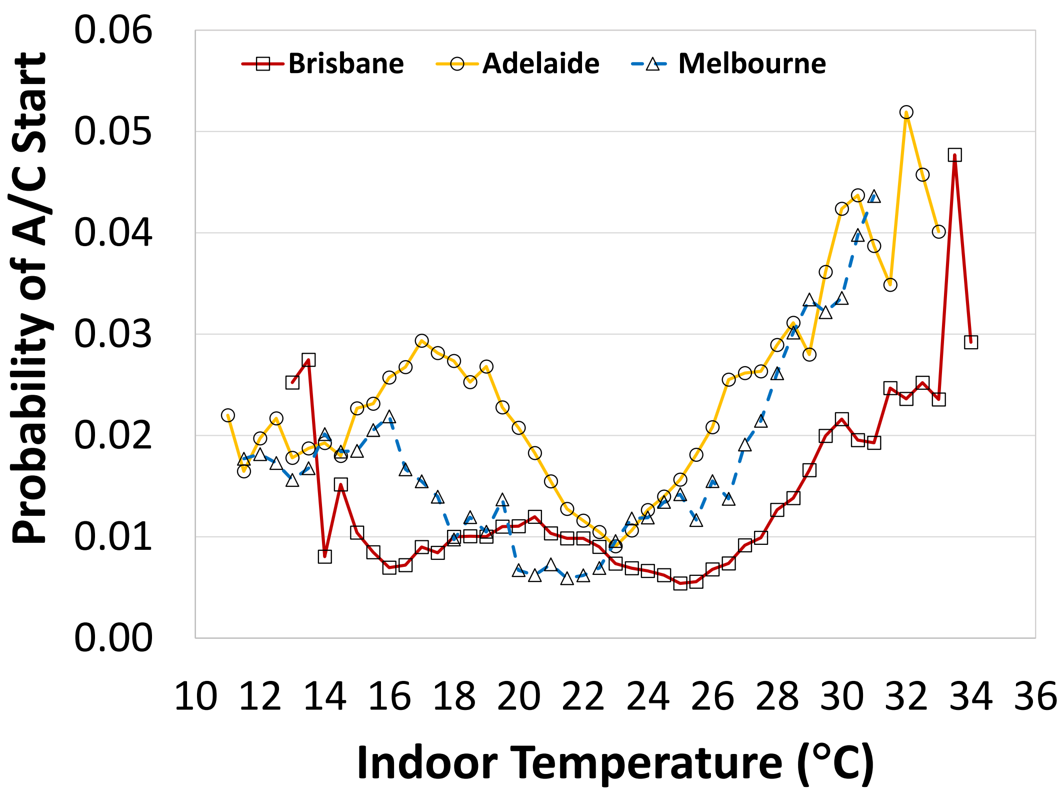


Figure 4. A/C "switch on" probability at different indoor air temperature in Brisbane, Adelaide and Melbourne

Figure 6 shows the relationship between the indoor air temperatures when A/C is switched on, i.e., $T_{switchon}$, and $T_{runningaverage}$ in Brisbane, Adelaide and Melbourne respectively. For each city, the left side plot shows the correlation including all the data points in the whole range of the running average outdoor temperature (referred to as single range plot hereafter). The right side plot shows the correlations if the running average outdoor temperature is divided into three ranges, the low range, the shoulder range and the high range (referred to as three range plot hereafter). These ranges are 10.1 - 15.5°C, 15.6 - 22.8°C, 22.9 - 27.5°C for Brisbane; 4.9 - 12.7°C, 12.8 - 22.0°C, 22.1 - 30.4°C for Adelaide; and 7.0 - 12.8°C, 12.9 - 19.5°C, 19.6 - 27.2°C for Melbourne respectively.

It was found that for the single range plot, the correlation slopes between $T_{switchon}$ and $T_{runningaverage}$ are between 0.63 and 0.74 for the three cities. However, for the three range plot, the correlation slopes between $T_{switchon}$ and $T_{runningaverage}$ are between 0.02 and 0.37 for the three cities for the low and the high ranges. Especially for Adelaide and Melbourne, the correlation slopes are all below 0.28 for the low and the high ranges. For the shoulder ranges, the correlation slopes are high at around 1.0 for the three cities. Figure 6 suggests that occupants are not very tolerant at the low and the high $T_{runningaverage}$ ranges, while they are more adaptive with the shoulder $T_{runningaverage}$ range which is a transition from relatively cold to hot outdoor air temperatures. This low tolerance at the low and the high $T_{runningaverage}$ range can be more clearly seen by the flat median (50-percentile) $T_{switchon}$ values at the low and the high $T_{runningaverage}$ ranges in the single range plots in Figure 6.

Figure 7 shows the relationship between $T_{switchon}$ and $T_{runningaverage}$ after combining all the data from the houses in the three cities. Similar to Figure 6, three ranges of the $T_{runningaverage}$ can be found. The correlation slope is 0.66 for single range plot, while they are 0.11, 0.89 and 0.24 for the low (4.9 – 13.0°C), shoulder (13.1 – 23.0°C) and the high ranges (23.1 – 30.4°C) respectively.

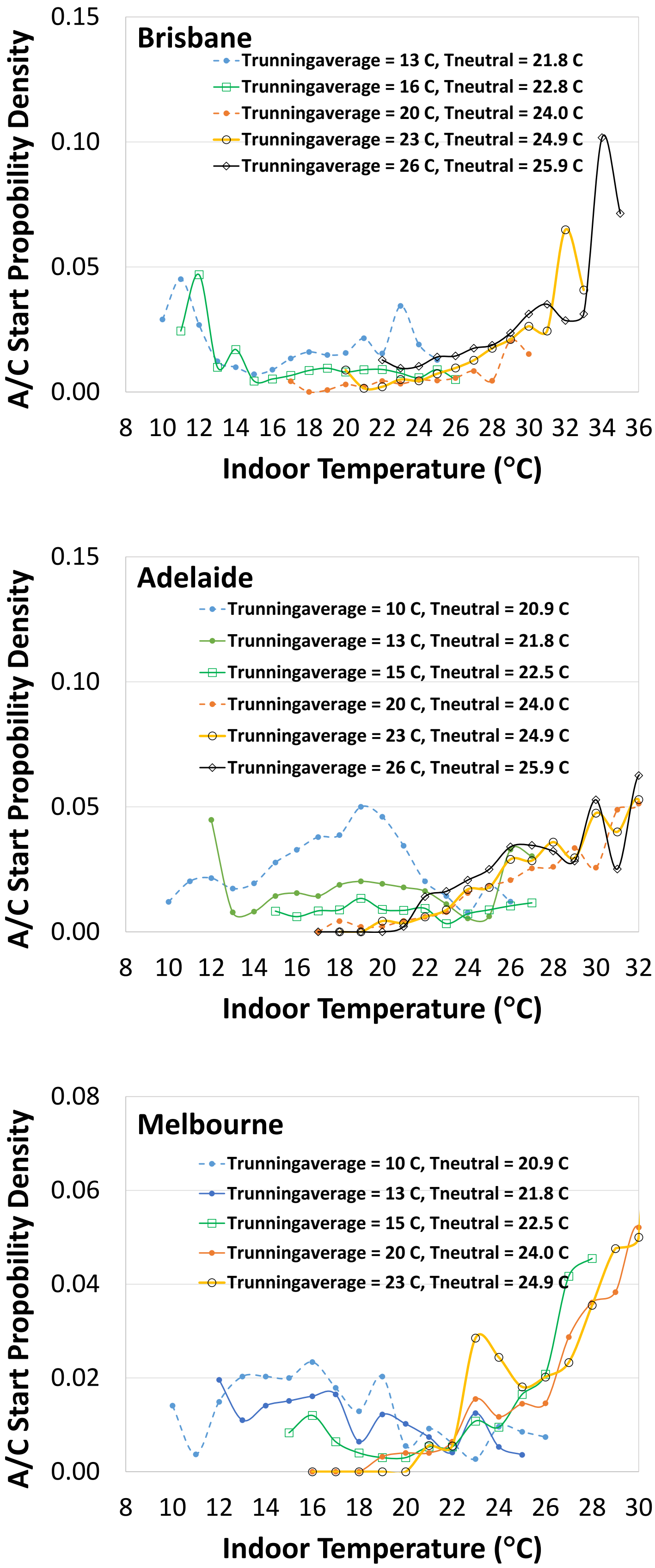


Figure 5. A/C "switch on" probability at fixed running outdoor average temperature at different indoor air temperature in Brisbane, Adelaide and Melbourne

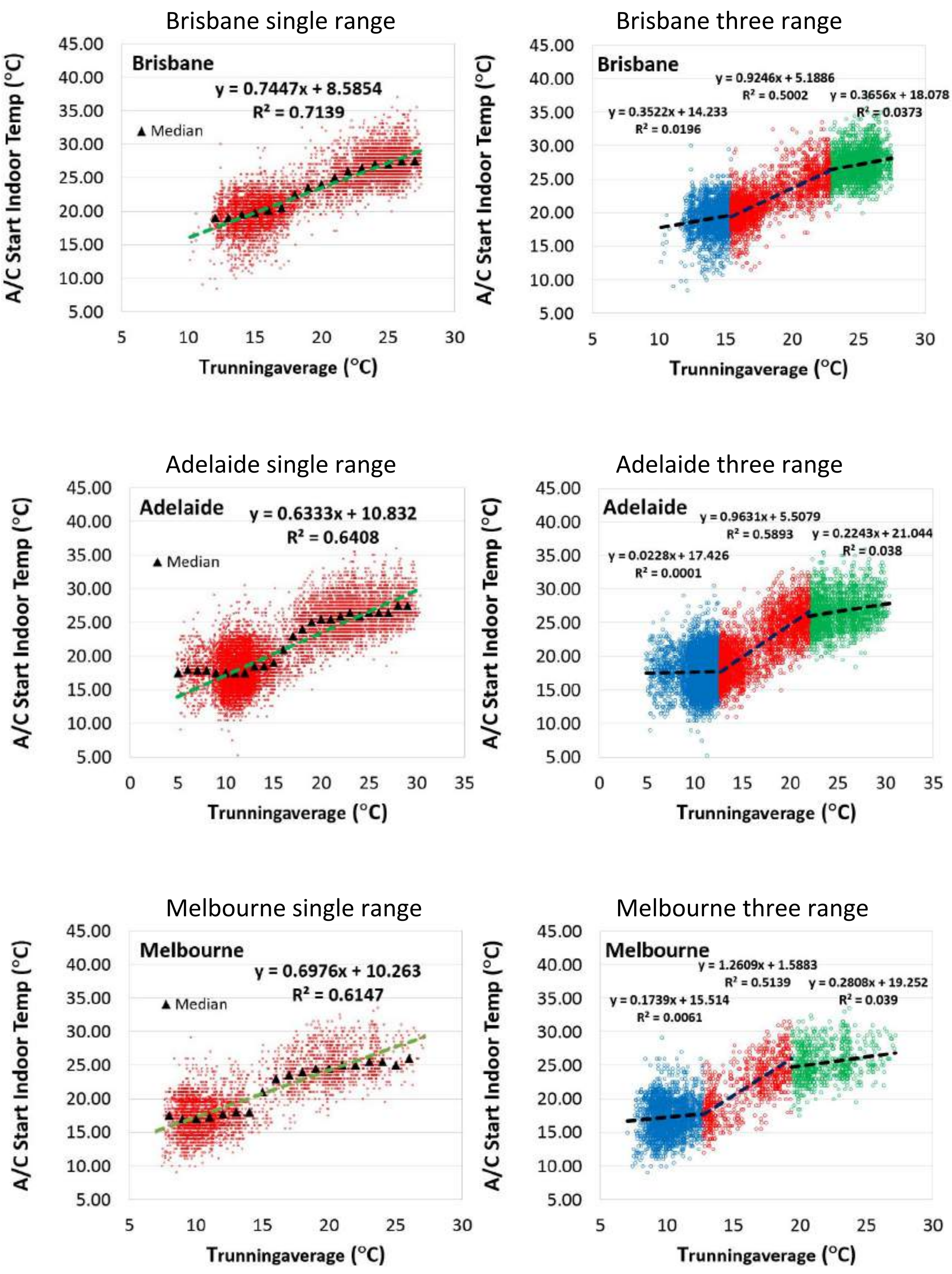
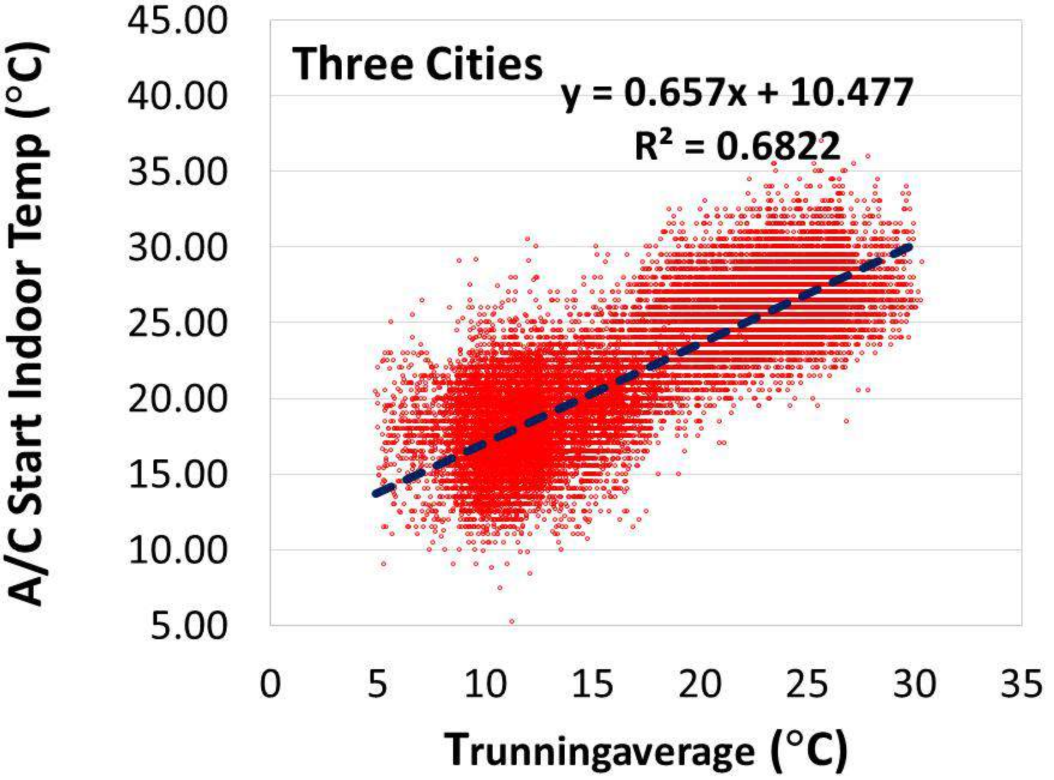
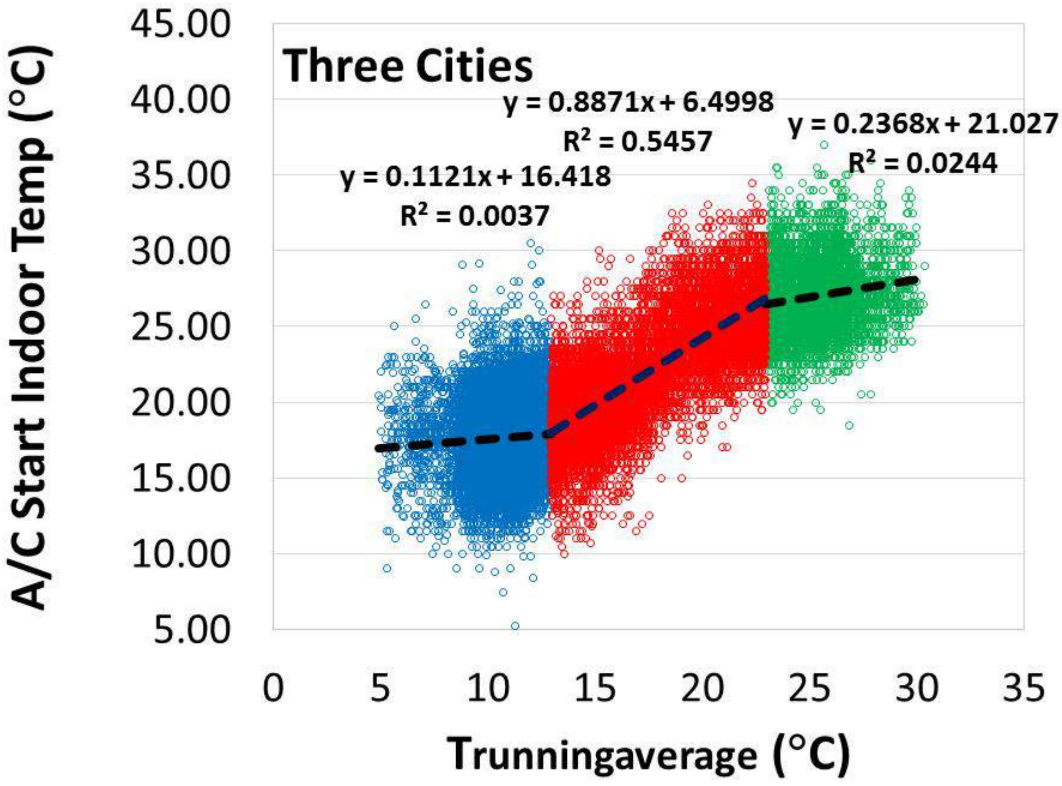


Figure 6. A/C “switch on” indoor air temperature at different running outdoor average temperature in Brisbane, Adelaide and Melbourne



(a)



(b)

Figure 7. A/C "switch on" indoor air temperature at different running outdoor average temperature using data from all the three cities: (a) single range plot; (b) three range plot.

3.3. A/C switching off temperatures

A/C may be switched off when the occupants judge the indoor environment can maintain comfortable without A/C running, or when the occupants leave the air conditioned space or the house. Kim et al (2016) discussed the A/C switch off indoor temperature (T_{off}) and considered that it may be a good approximation of occupants' comfort temperature. Figure 8 shows the relationship between T_{off} and $T_{runningaverage}$ for Brisbane, Adelaide and Melbourne respectively. The left side shows the single range plot and the right side shows the three range plot. The single range plots also include the neutral temperature $T_{neutral}$ calculated by Eq. (1) based on the ASHRAE adaptive thermal comfort model.

It is seen that, in general, the correlations for the three cities are not far from the neutral temperature predicted by the ASHRAE adaptive thermal comfort model. The slightly higher correlation slopes from the measured T_{off} in comparison with $T_{neutral}$ may be due to several factors: 1) occupants do not heat or cool the living room to the neutral temperature since slightly cold (during heating) and slightly warm (during cooling) are acceptable; 2) the A/C capacity is not sufficient to heat or cool the living room to the neutral temperature; 3) due to the cost of running A/C at high capacity, and so on. Similar to A/C switch on, Figure 8 again shows the existence of three $T_{runningaverage}$ ranges: a low, a shoulder and a high range for each climates. At the low and the high ranges, the occupants have less tolerance to the thermal environment, while the occupants are more adaptive in the shoulder range.

3.4. The relationship between A/C switch on and A/C operation indoor temperatures

Figure 9 shows the relationship between the average $T_{switchon}$ and the average A/C operation indoor temperature $T_{operation}$ for each house in winter and summer in Brisbane, Adelaide and Melbourne respectively. It is seen that occupants operate houses in significantly wide ranges of average heating and cooling indoor temperatures. For heating, this was from 12 to 25 °C. For cooling, it was from 22 to 31°C. It is also seen that the average $T_{switchon}$ and the average $T_{operation}$ are well correlated. It means that occupants who switch on A/C at low indoor temperatures prefer running A/C at low indoor temperatures. The opposite is true that occupants who switch on A/C at high indoor temperatures prefer running A/C at high indoor temperatures.

Figure 10 shows the relationship between a house's average $T_{switchon}$ in the winter and its corresponding average $T_{switchon}$ in the summer for all the houses in the three cities. Figure 11 shows the relationship between the average $T_{operation}$ in winter and summer for the three cities. Figures 10 and 11 suggest that there is no relationship between occupants' winter cool sensation and their summer warm sensation. This means that an occupant who prefers running A/C at a relatively high indoor temperature in summer does not mean the occupant will prefer running A/C at a relatively high or low indoor temperature in winter.

3.5. A/C operation indoor temperature band

Figure 12 shows the living room temperature when A/C is running as a function of $T_{runningaverage}$: minimum, maximum, 95-, 50-, and 5-percentiles for the houses in the three cities. It is seen that except those low $T_{runningaverage}$ where the measurements are sparse and the shoulder $T_{runningaverage}$ range, the median (50%) indoor temperature are relatively flat for cooling and heating. This trend is similar to that reported by Peeters et al. (2009) for Belgian dwellings. Figure 12 also includes the neutral temperature line for the ASHRAE adaptive model, i.e. Eq. (1). It is interesting to see that the median indoor temperatures when A/C is in operation for the three cities are spread around the ASHRAE adaptive model line, except that the median indoor temperatures flatten out at the low and high $T_{runningaverage}$ ranges.

Combining the findings above for T_{off}, the indoor temperature clouds during A/C operation may suggest that occupants' thermal comfort in the heated and cooled houses in these three cities may be not far from the ASHRAE adaptive model, however, there are obviously limits existing at the low and high $T_{runningaverage}$ ranges.

Table 1 lists the average median indoor temperature, the 80-percentile (from 10-percentile to 90-percentile) and the 90-percentile temperature (from 5-percentile to 95-percentile) bands for the three cities for heating and cooling respectively. In the brackets in Table 1, the positive value is the upper band and the negative value is the lower band. It is seen that the median heating indoor temperatures are between 20.0 and 21.2°C. In general, the temperature band for heating is wider than that for cooling. This is in agreement with that reported by Peeters et al. (2009) for Belgian dwellings. In average, the 80-percentile indoor air temperature bands are 7.3°C and 6.2°C for heating and cooling respectively. The 90-percentile indoor air temperature bands are 9.3°C and 7.8°C for heating and cooling respectively which is within the ranges reported by Nicol (2017) for residential buildings.

Table 1. average median indoor temperature and 80-, 90-percentile temperature bands when A/C runs

	Average Median Temperature [ºC]		**Average 80% percentile band [ºC]**		**Average 90% percentile band [ºC]**	
	Heating	**Cooling**	**Heating**	**Cooling**	**Heating**	**Cooling**
Brisbane	**21.2**	**27.1**	**7.7(4.1,-3.6)**	**6.2(2.9,-3.3)**	**9.8(5.2,-4.6)**	**7.8(4.0,-3.8)**
Adelaide	**20.6**	**26.1**	**7.1(2.8,-4.3)**	**6.1(3.4,-2.7)**	**9.0(3.7,-5.3)**	**7.8(4.4,-3.4)**
Melbourne	**20.0**	**26.1**	**7.0(3.2,-3.8)**	**6.2(3.2,-3.0)**	**9.0(4.0,-5.0)**	**7.9(4.1,-3.8)**

3.6. Implications for energy efficient building regulations

The findings of the current study may have several implications to the development and improvement on the regulations of Australian house energy efficiency in terms of occupant thermal comfort and A/C operation assumptions. It is very likely that the existing static thermostat setting approach will continue to be used in the *AccuRate* software for house energy rating in Australia for the foreseeable three to five years. The findings in this study that occupants are relatively not thermally tolerant and the $T_{switchon}$, $T_{operation}$, T_{off} are relatively flat at the low and high $T_{runningaverage}$ ranges do support such simplifications before a more reliable dynamic thermostat setting approach can be established.

Table 2 lists the average median $T_{switchon}$, $T_{operation}$, T_{off} for heating and cooling for the three cities. In the brackets are the existing assumed thermostat settings in *AccuRate* for house energy rating calculations. For heating, the thermostat of 20°C in the living room appears reasonable for Melbourne, but is about 0.6°C and 1.2°C lower for Adelaide and Brisbane respectively. However, the heating switch on temperatures in Adelaide and in Melbourne in the existing *AccuRate* software for living room is too high and a switch on indoor temperature of around 17.5°C may be more adequate. For cooling, the average median cooling switch on temperature are around 0.5°C lower than the currently assumed values for the three cities. However, the median indoor temperatures, when A/C is running which may be considered as the real thermostat set point, are about 1.5°C above the currently assumed values for the three cities. Of course, it is arguable whether it is adequate to use the average median $T_{switchon}$ and $T_{operation}$ for setting the A/C triggering indoor temperature and the thermostat set point temperature. Further research is needed.

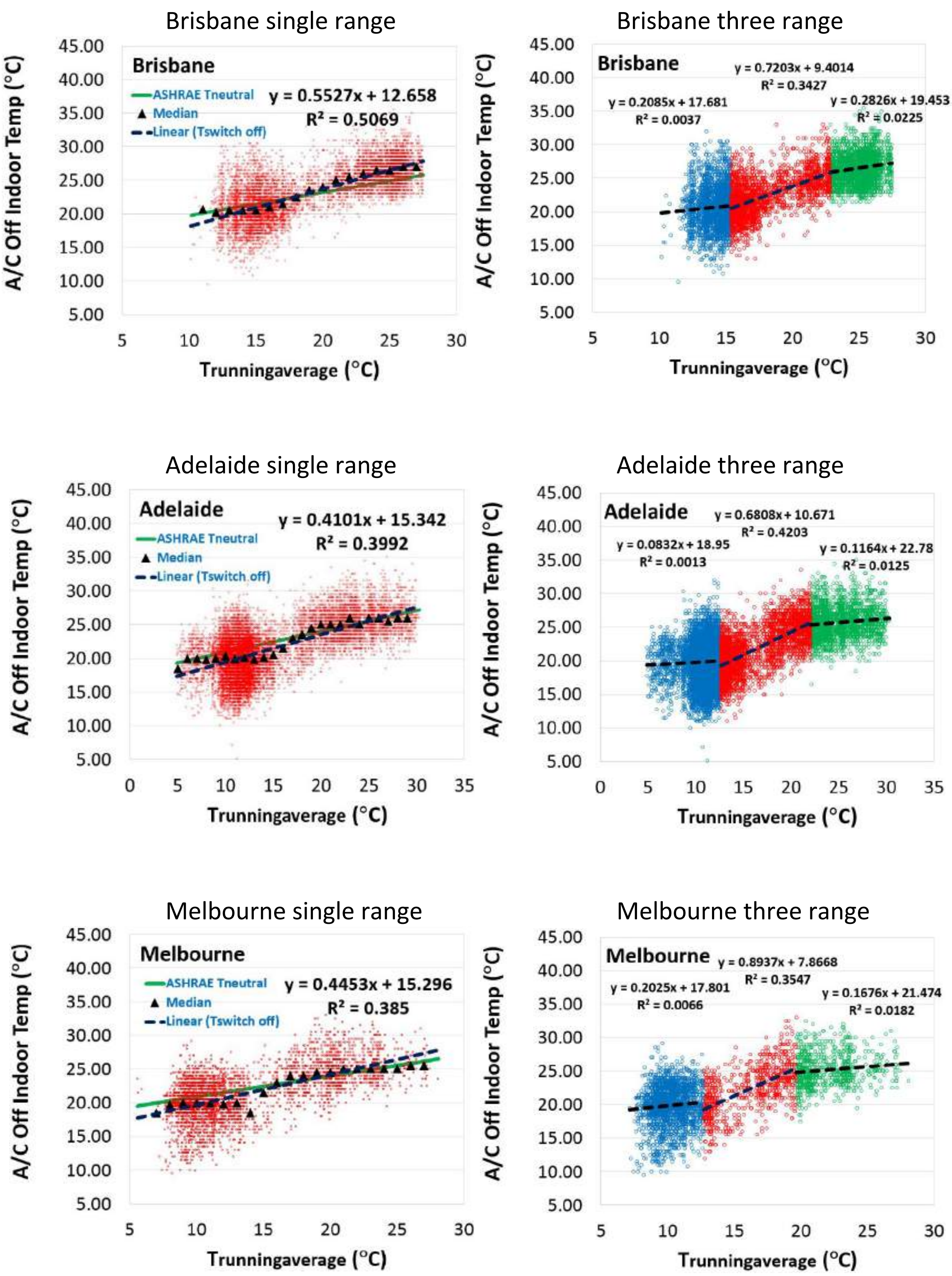


Figure 8. A/C “switch off” indoor air temperature at different running outdoor average temperature in Brisbane, Adelaide and Melbourne

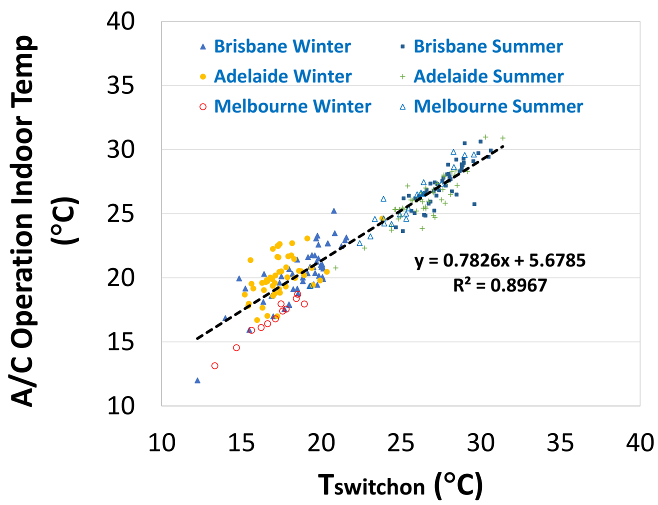


Figure 9. Relationship between the average A/C switch on indoor temperature and the average A/C operation indoor air temperature for each house in winter and summer

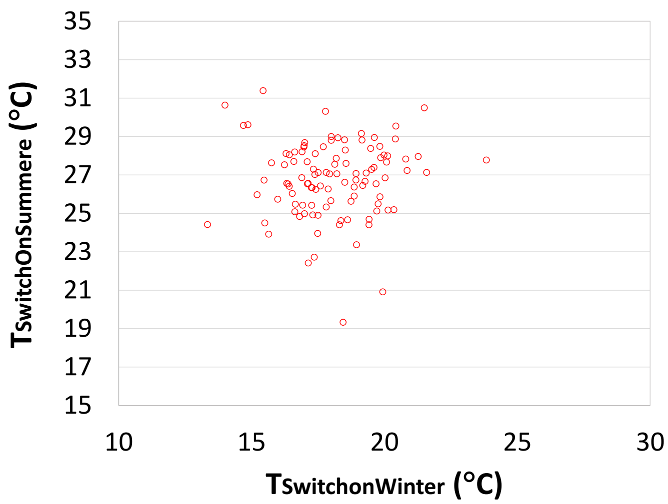


Figure 10. Relationship between A/C “switch on” indoor air temperatures in the winter and summer for the three cities

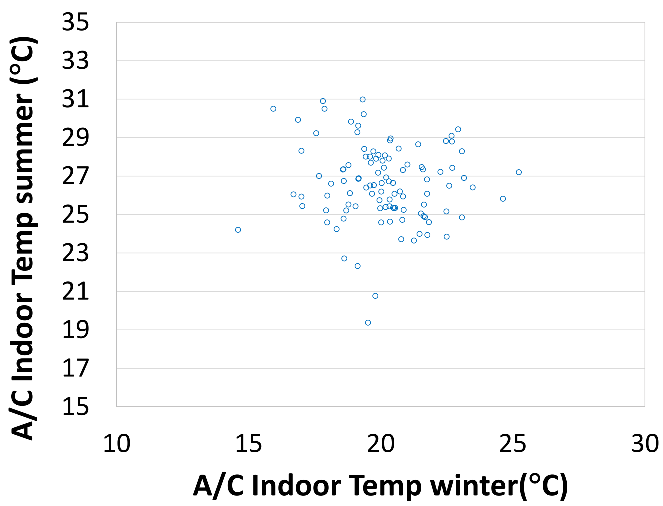


Figure 11. Relationship between A/C operation indoor air temperatures in the winter and summer for the three cities

Table 2. average median $T_{switchon}$, $T_{operation}$, T_{off} for heating and cooling for the three cities (In the brackets are the existing assumed thermostat settings in *AccuRate* for house energy rating calculations)

	Average Median $T_{switchon}$ [ºC]		**Average Median $T_{operation}$ [ºC]**		**Average Median T_{off} [ºC]**	
	Heating	**Cooling**	**Heating**	**Cooling**	**Heating**	**Cooling**
Brisbane	**19.5(20.0)**	**27.6(28.0)**	**21.2(20.0)**	**27.1(25.5)**	**20.5(20.0)**	**27.1(25.5)**
Adelaide	**17.7(20.0)**	**26.8(27.5)**	**20.6(20.0)**	**26.1(25.0)**	**20.1(20.0)**	**26.1(25.0)**
Melbourne	**17.2(20.0)**	**26.2(26.5)**	**20.0(20.0)**	**26.1(24.0)**	**19.9(20.0)**	**25.6(24.0)**

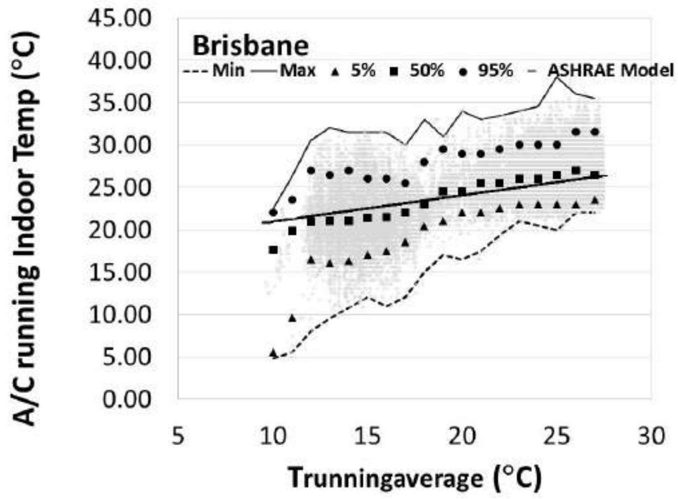
It is noted that the current research only provide one angle of the understanding of thermal comfort and occupants' A/C operation behaviours in houses. The study has at least the following limitations:

1. The number of houses investigated are limited and data points are not enough as can be seen in Figure 5;
2. Measurements were only taken for air temperatures in the living room. Indoor relative humidity, mean radiant temperatures and air movement velocity were not measured. Further, indoor temperatures in bedrooms are likely different from those in living rooms;
3. Thermal comfort surveys were not carried out in this study.

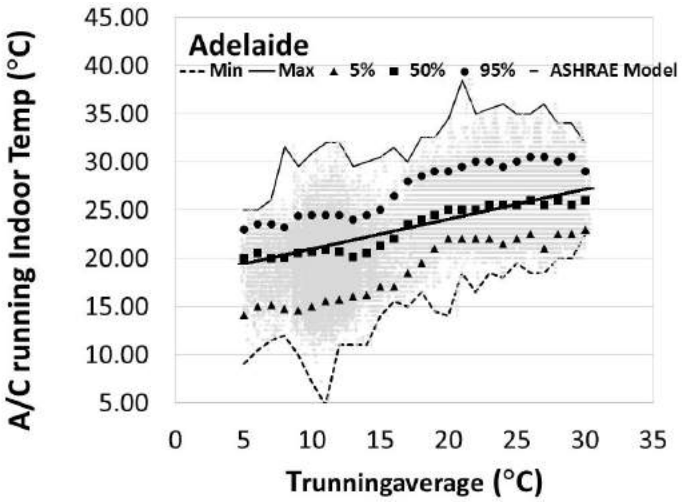
Considering the importance of thermal comfort and A/C operation in house energy efficiency regulation development, further research is needed to validate and improve the understanding in both occupants' thermal comfort and A/C operation behaviours in Australian residential houses.

4. Conclusions

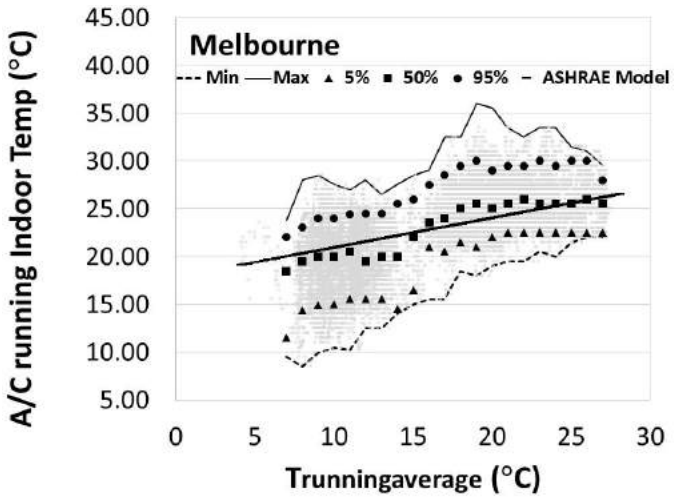
This study analysed over 1.8 million measurements of air conditioner power consumption and indoor/outdoor air temperatures in 129 houses in Adelaide, Brisbane and Melbourne from 2012 to 2014. It was found that A/C is most unlikely to be switched on at around 20-22.5°C, 21.5-24°C and 23.5-26°C indoor temperature ranges in Melbourne, Adelaide and Brisbane respectively. This is in line with thermal adaption to the local climates. In each climate, the A/C switch on indoor temperatures, the A/C switch off indoor temperatures and the A/C in operation indoor temperatures can be grouped into three $T_{runningaverage}$ ranges: the low range, the shoulder range and the high range. Occupants are not very tolerant at the low and high $T_{runningaverage}$ ranges, while they are more adaptive with the shoulder temperature range. Findings in this study support the simplified static thermostat setting approach used in *AccuRate*, though the existing thermostat settings should be adjusted. More research is required for better understanding thermal comfort and A/C operation behaviours in residential houses for developing building regulations for more comfortable and energy efficient housing in Australia.



(a) Brisbane



(b) Adelaide



(c) Melbourne

Figure 12. Living room temperature when A/C in running as a function of $T_{runningaverage}$: minimum, maximum, 95-, 50-, and 5-percentiles

5. References

ABCB, 2006, *Protocol for House Energy Rating Software*. Australian Building Codes Board.

Alshaikh, A., & Roaf, S. 2016. Designing comfortable, low carbon, homes in Dammam, Saudi Arabia: The roles of buildings and behaviours. Proceedings of 9th Windsor Conference: Making Comfort Relevant, Cumberland Lodge, Windsor, UK, 7–9 April 2016, Network for Comfort and Energy Use in Buildings.

Ambrose, M., James, M., Law, A, Osman, P., White, S., 2013. The Evaluation of the 5-Star Energy Efficiency Standard for Residential Buildings, CSIRO report, Melbourne, Australia.

ASHRAE, 2013. *ANSI/ASHRAE Standard 55-2013: Thermal Environmental Conditions for Human Occupancy*. American Society of Heating, Refrigeration and Ai-Conditioning Engineers Inc., Atlanta.

Beckett, C.T.S., Cardell-Oliver, R., Ciancio, D., Huebner, C., 2017, Measured and simulated thermal behaviour in rammed earth houses in a hot-arid climate. Part B: Comfort. *Journal of Building Engineering* 13, 146–158.

Daniel, L., Williamson, T., Soebarto, V., Chen, Z.D., 2015, Learning from thermal mavericks in Australia: comfort studies in Melbourne and Darwin. *Architectural Science Review* 58(1) 57-66.

de Dear, R.J., & Brager, G., 1998. Developing an adaptive model of thermal comfort and preference, *ASHRAE Transactions* 104(1), 145-167.

de Dear, R.J., & Brager, G., Cooper, D., 1997. *Developing an adaptive model of thermal comfort and preference*, Final report ASHRAE RP-884.

De Dear, R.J., 1998, A global database of thermal comfort field experiments. *ASHRAE Transactions*, 104, 1141-1152.

Delsante, A., 2005. Is the new generation of building energy rating software up to the task? - A review of AccuRate. *ABCB Conference 'Building Australia's Future 2005'*, Surfers Paradise, 11-15 September 2005.

DOEE, 2017. *Australian Energy Update 2017*, https://www.energy.gov.au/sites/g/files/net3411/f/energy-update-report-2017.pdf, Department of Environmental and Energy (DOEE).

James, P., Sonne, J., Vieira, R., Parker, D., Anello, M., 1996. Are energy savings due to ceiling fans just hot air? *Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings* 8, 89-93.

Kim, J., de Dear, R.J., Parkinson, T., Candido, C., Cooper, P., Ma, Z., Saman, W., 2016. Field study of air conditioning and thermal comfort in residential buildings. *Proceeding of 9th Windsor Conference: Making Comfort Relevant*, Cumberland Lodge, UK, April 7-10, 2016.

Lomas, K. J., Kane, T., 2013. Summertime temperatures and thermal comfort in UK homes, *Building Research & Information* 41(3), 259-280

Manning, M.M., Swinton, M.C., Szadkowski, F., Gusford, J., Ruest, K., 2007. The Effects of Thermostat Setback and Setup on Seasonal Energy Consumption, Surface Temperatures, and Recovery Times at the CCHT Twin House Research Facility, *ASHRAE Transactions* 113(1), 1-12.

Nicol, F., 2017. Temperature and adaptive comfort in heated, cooled and free-running dwellings, Building Research & Information, 45:7, 730-744

Peeters, L., de Dear, R., Hensen, J., & d'Haeseleer, W., 2009. Thermal comfort in residential buildings: comfort values and scales for building energy simulation. *Applied Energy*, 86, 772–780.

Ren, Z., & Chen, Z.D., 2010. Enhanced Air Flow Modelling for AccuRate – A Nationwide House Energy Rating Tool in Australia. *Building and Environment* 45 (5): 1276–1286.

Ren, Z., & Chen, Z.D., 2017. Modelling study of the impact of thermal comfort criteria on housing energy use in Australia. *Applied Energy*, https://doi.org/10.1016/j.apenergy.2017.10.110.

Shiel, J., Aynsley, R., Moghtaderi, B., Page, A., 2017. The importance of air movement in warm temperatures: a novel SET* house case study. *Architectural Science Review* 60, 225-238.

Walsh, P.J., & Delsante, A.E., 1983. Calculation of the thermal behaviour of multi-zone buildings, *Energy and Buildings* 5: 231-242.

SESSION 6

Comfort in Different Conditions

Invited Chairs:
Eduardo Krüger and Cao Bin

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Adaptive Mechanisms for Thermal Comfort in Japanese Dwellings

H.B. Rijal[1], M.A. Humphreys[2] and J.F. Nicol[3]

[1] Tokyo City University, Japan, rijal@tcu.ac.jp
[2] Oxford Brookes University, UK, mahumphreys@brookes.ac.uk
[3] Oxford Brookes University, UK, jfnicol@brookes.ac.uk

Abstract: In order to quantify the seasonal differences in the comfort temperature and to develop a domestic adaptive model for Japanese dwellings, thermal measurements, a thermal comfort survey, and an occupant behaviour survey were conducted for 4 years in the living and bedrooms of dwellings in the Kanto region of Japan. We have collected 36,114 thermal comfort votes from 244 residents of 120 dwellings. The results show that the residents are highly satisfied with the thermal environment of their dwellings. People are highly adapted in the thermal condition of the dwellings, and thus the comfort temperature has large seasonal differences. An adaptive model for housing was derived from the data to relate the indoor comfort temperature to the prevailing outdoor temperature. Such models are useful for the control of indoor temperatures. The adaptive model of thermal comfort is highly supported by the various adaptive mechanisms.

Keywords: Japanese dwellings; Field survey; Comfort temperature; Adaptive model; Adaptive mechanism

1. Introduction

This paper presents the data from a long-term survey of the thermal conditions and thermal comfort in 120 Japanese dwellings. It explores the ways by which the occupants achieve thermal comfort, by opening or closing windows, by using fans and by turning heating or cooling on or off. The way indoor comfort is related to the prevailing outdoor temperature is also explored and quantified, to supply an 'adaptive model' [1] specifically applicable to Japanese homes.

Indoor temperatures are an important factor in creating comfortable homes. An understanding of the locally required comfort temperature can be useful in the design of dwellings and their heating and cooling systems to avoid excessive energy use.

Comfort temperatures in dwellings have been widely investigated, with studies in Japan (Nakaya et al. 2005, Rijal et al. 2013), Nepal (Rijal et al. 2010), Pakistan (Nicol & Roaf 1996) and UK (Rijal & Stevenson 2010). However, there are limitations to this research, with some studies being short, and some based on small samples. Comfort temperatures vary according to the month and season, and so they need long-term data to establish the seasonal changes in people's perceptions of indoor temperature and their behavioural responses to it.

In 2004 ASHRAE introduced into Standard 55 (Thermal environment conditions for human occupancy) an adaptive model applicable to naturally ventilated buildings (ASHRAE 2004), and in 2007 CEN (2007) proposed, in their Standard EN 15251, a similar adaptive model for free-running naturally ventilated buildings. However, the data underlying these standards did not include any data from Japanese dwellings. Also, most of the data were

[1] By 'adaptive model' we mean an equation relating the prevailing outdoor temperature to the temperatures found comfortable indoors.

from offices. Occupant behaviour is different in the office and at home, and so neither of these two adaptive models can be assumed to apply to Japanese homes.

An adaptive model shows that the comfort temperature indoors is related to the outdoor temperature, but being a 'black box' statistical model, it does not reveal its internal workings. We know the input to the 'black box' and the output from it, but we don't fully know the mechanisms behind it. Adaptive thermal comfort depends on behavioural, physiological and psychological adaptations. Residents use a variety of adaptive opportunities to regulate their indoor thermal environment. We need to explore their adaptive actions to give support to the adaptive model set out in this paper[2].

2. Field investigation

To develop a domestic adaptive model and to quantify the adaptive mechanisms for Japanese dwellings, thermal measurements and thermal comfort surveys were conducted in the living and bedrooms of 120 dwellings in the Kanto region of Japan (Kanagawa, Tokyo, Saitama and Chiba) from 2010 to 2014 (Rijal et al. 2015).

Table 1 shows the survey periods. The indoor air temperature and the relative humidity were measured in the living rooms and bedrooms, away from direct sunlight, at ten minute intervals using a data logger (see Figure 1 and Table 2). In addition, the globe temperature was measured in the living room in surveys 3 to 5. The number of subjects was 119 males and 125 females. Respondents completed a questionnaire several times a day in the living rooms, and twice in the bedroom (before going to bed and after waking-up) (Table 3).

The thermal comfort survey was conducted in Japanese. The subjective scales are shown in Table 3. The ASHRAE scale is frequently used to evaluate the thermal sensation vote (TSV), but the words 'warm' or 'cool' imply comfort in Japanese, and thus the modified thermal sensation vote (mTSV) was also used to evaluate the thermal sensation (Table 3). To avoid a possible misunderstanding of 'neutral', it was explained in the questionnaire as 'neutral (neither hot nor cold)'. It is also said that the optimum temperature occurs on the cooler side in summer and on the warmer side in winter (McIntyre 1980), and so the scales of warmth sensation were supplemented by a scale of thermal preference. The window opening, fan/cooling/heating use was recorded in binary form several times in a day. We collected a total of 36,114 sets of thermal comfort votes over the four years. Outdoor air temperature and relative humidity were obtained from the nearest meteorological station.

Table 1. Description of survey

Survey	Survey period		Surveyed room	Measured variables*	No. of dwellings	No. of subjects			No. of votes	
	Start date	End date				Male	Female	Total	Living	Bedroom
1	06-7-2010	18-7-2011	Living, Bed	T_i, RH_i	11	16	14	30	3,300	2,558
2	05-8-2011	06-9-2011	Living	T_i, RH_i	59	52	57	109	2,861	-
3	21-7-2011	08-5-2012	Living, Bed	T_i, RH_i, T_g	10	11	12	23	463	984
4	25-7-2012	24-6-2013	Living, Bed	T_i, RH_i, T_g	30	26	28	54	13,083	7,061
5	10-8-2013	09-8-2014	Living, Bed	T_i, RH_i, T_g	10	14	14	28	2,679	3,125
Total					120	119	125	244	22,386	13,728

T_i: Indoor air temperature (°C), RH_i: Indoor relative humidity (%), T_g: Indoor globe temperature (°C), *: T_g is measured only in the living room.

[2] IEA EBC Annex 69 is also trying to address these issues.

Table 2. Description of the instruments

Parameter measured	Trade name	Range	Accuracy
Air temperature, RH	TR-74Ui	0 to 55 °C, 10 to 95% RH	±0.5 °C, ±5%RH
Air temperature, RH	RTR-53A	0 to 55 °C, 10 to 95% RH	±0.3 °C, ±5%RH
Globe temperature*	Tr-52i	−60 to 155 °C	±0.3 °C
	SIBATA 080340-75		-

RH: Relative humidity. * Black painted 75 mm diameter globe

Table 3. Questionnaires for thermal comfort survey

No.	TSV	mTSV (literal English translation)	Thermal preference	Skin moisture
1	Cold	Very cold	Much warmer	None
2	Cool	Cold	A bit warmer	Slightly
3	Slightly cool	Slightly cold	No change	Moderate
4	Neutral (neither cool nor warm)	Neutral (neither cold nor hot)	A bit cooler	Profuse
5	Slightly warm	Slightly hot	Much cooler	-
6	Warm	Hot	-	-
7	Hot	Very hot	-	-

TSV: Thermal sensation vote, mTSV: modified thermal sensation vote.

Figure 1. Details of the thermal measurement.

3. Results and analysis

The dwellings could be described as 'mixed mode' (MM), in that heating and cooling were available, but used only when the occupants felt the need of them. The data were divided into three groups. If heating was in use at the time of the voting, the data were classified as being in the heating mode (HT). If cooling was in use at the time of the voting, the data were classified as being in the cooling mode (CL). If neither heating nor cooling were in use, the data were classified as being in the free-running mode (FR). The CL and HT modes are distinct groups of data. Generally cooling was used only in summer and heating only in winter). Data from the CL and HT modes were kept separate during analysis[3].

3.1. Thermal environment at the times of voting

The seasonal range of the indoor temperature and outdoor air temperature was quite large (Figure 2). The mean indoor air temperatures and globe temperatures were almost the same (Figure 2, Table 4). The Japanese government recommends indoor temperature

[3] The classification differs from that used in the CIBSE Guide (CIBSE 2006), and in current ISO Standard EN 15251 and ASHRAE Standard 55.

settings of 20 °C in winter and 28 °C in summer. The results show that the mean indoor temperatures during heating and cooling were close to this recommendation.

Figure 3 shows the relation between the indoor and outdoor air temperature. The indoor air temperature in FR mode has a wider range than either the CL mode or the HT mode. We obtained the following regression equations relating the indoor temperature to the outdoor temperature:

FR T_i=0.587T_o+12.6 (n=25,180, R^2=0.78, S.E.=0.002, p<0.001) (1)

CL T_i=0.183T_o+22.3 (n=6,531, R^2=0.07, S.E.=0.008, p<0.001) (2)

HT T_i=0.220T_o+17.4 (n=3,582, R^2=0.10, S.E.=0.011, p <0.001) (3)

Note: T_i is indoor air temperature (°C), T_o is outdoor air temperature (°C), n is number of sample, R^2 is coefficient of determination, S.E. is standard error of the regression coefficient and p is significance level of regression coefficient.

As would be expected, the indoor temperature in the free-running mode is much more dependent on the outdoor temperature than it is in the other modes. Similarly the correlation coefficient (Table 5) for the FR mode is much higher than for the CL or HT mode.

Figure 4 shows the relation between the indoor globe temperature (T_g) and indoor air temperature. As expected, they are very highly correlated (Table 5). Because of these very high correlations, and because the globe temperature was recorded in only some of the surveys, the analysis continues using air temperature as the measure of the indoor environment. We have obtained the following regression equations.

FR T_g=0.992T_i+0.2 (n=10,913, R^2=0.99, S.E.=0.001, p <0.001) (4)

CL T_g=0.874T_i+3.5 (n=2,680, R^2=0.84, S.E.=0.007, p<0.001) (5)

HT T_g=0.938T_i+1.4 (n=2,256, R^2=0.83, S.E.=0.009, p<0.001) (6)

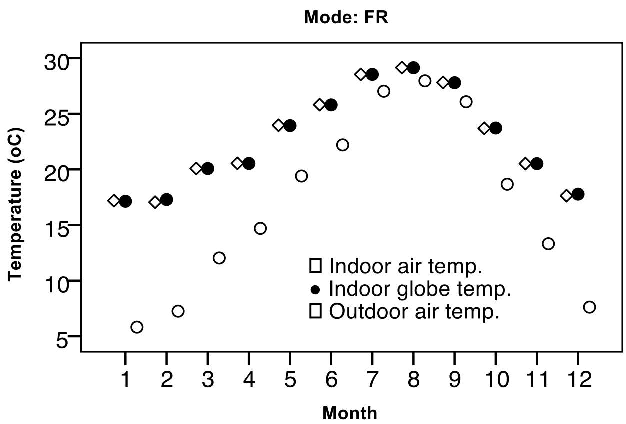


Figure 2. Monthly mean temperature in FR mode

Table 4. Temperatures and relative humidity in various modes.

Variables	FR			CL			HT		
	N	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.
Indoor air temp. (°C)	25,195	23.7	5.3	6,532	27.3	1.9	3,582	18.9	2.9
Indoor globe temp. (°C)	11,012	23.5	4.5	2,951	27.6	1.7	2,256	19.6	2.8
Outdoor air temp. (°C)	25,339	18.9	8.0	6,802	27.6	2.7	3,604	7.2	4.2
Indoor relative humidity (%)	25,195	59	11	6,532	57	9	3,582	48	11
Outdoor relative humidity (%)	24,495	68	18	6,789	76	11	3,603	56	19

N: Number of sample, S.D.: Standard deviation

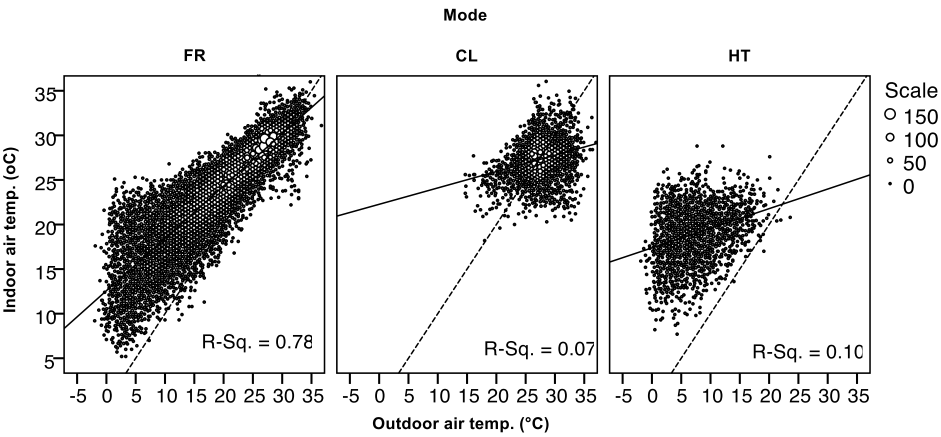


Figure 3. Relation between the indoor and outdoor air temperature.

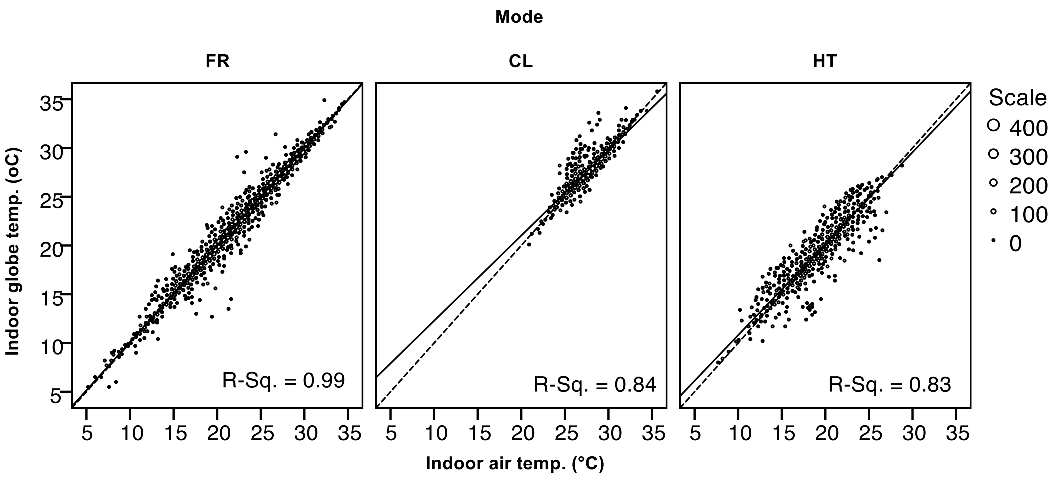


Figure 4. Relation between the indoor globe temperature and indoor air temperature.

Table 5. Correlation coefficients in various modes.

Mode	Items	$T_i : T_o$	$T_g : T_o$	$T_i : T_g$	RH_i:RH_o
FR	r	0.89	0.84	0.99	0.52
	n	25,180	11,004	10,913	24,336
CL	r	0.26	0.35	0.92	0.17
	n	6,531	2,951	2,680	6,518
CL	r	0.31	0.23	0.91	0.18
	n	3,582	2,256	2,256	3,581

T_i: Indoor air temp. (°C), T_g: Indoor globe temp. (°C), T_o: Outdoor air temp. (°C),°C RH_i: Indoor relative humidity (%), RH_o: Outdoor relative humidity (%), p<0.001, p: Significant level, r: Correlation coefficient, n: Number of sample

3.2. Comparing the two thermal sensation scales

In this section we show that the modified thermal sensation scale (mTSV) is better than the ASHRAE scale (TSV) in these data. We regressed the thermal responses on the indoor air temperature. Tables 6 and 7 compare the regression statistics. It is apparent that the thermal sensation when expressed on the mTSV scale correlates much more closely with the indoor air temperature than it does when expressed on the TSV scale. It consequently has a smaller residual standard deviation, which indicates that people agree more closely on their thermal sensation at any particular temperature when this scale is used (i.e. their responses are more similar). The regression coefficients are similar for the two scales. The mTSV is more smoothly related than is the TSV to the thermal preference (Figure 5). It was concluded that the mTSV scale is superior to the TSV scale for these data, and it is therefore used to present the analysis.

Table 6. Regression analysis of thermal sensation or thermal preference and indoor air temperature.

Scale	Number of votes	Regression coefficient/K	Correlation coefficient	Residual standard deviation of vote	Overall standard deviation of vote
TSV	22,776	0.124	0.48	1.06	1.21
mTSV	35,337	0.110	0.63	0.70	0.90
Preference	32,876	0.090	0.63	0.56	0.72

TSV: Thermal sensation vote, mTSV: modified thermal sensation vote

Table 7. Correlation coefficients of the TSV or mTSV and each variable.

Mode	Items	TSV		mTSV	
		TP	T_i	TP	T_i
FR	r	0.79	0.60	0.86	0.68
	n	15,436	15,259	23,465	25,177
CL	r	0.70	0.24	0.80	0.28
	n	5,100	4,750	6,447	6,528
HT	r	0.70	0.18	0.79	0.30
	n	2,785	2,724	3,578	3,582

TP: Thermal preference, T_i: Indoor air temp. (°C), p<0.001, p: Significant level, r: Correlation coefficient, n: Number of sample

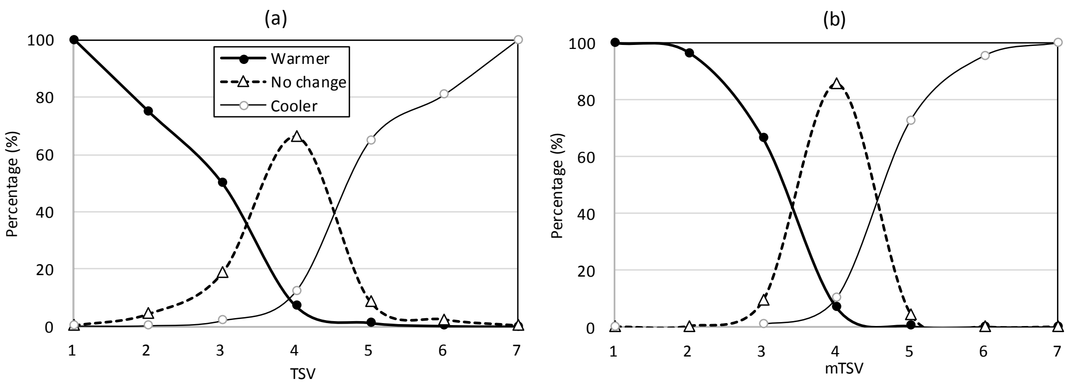


Figure 5. Relation between the thermal sensation and thermal preference. The ‘warmer’ includes ‘a bit warmer’ and ‘much warmer’ and the ‘cooler’ includes ‘a bit cooler’ and ‘much cooler’. The ‘warmer’ or ‘cooler’ line is the cumulative percentage and ‘no change’ line is the actual percentage for each thermal sensation vote.

3.3. Distribution of thermal sensation

Table 8 shows the percentages of thermal sensation in each scale-category for each mode. Even when the residents used the heating or cooling, they sometimes felt ‘cold’ or ‘hot’. The table shows that the residents were generally satisfied with the thermal environment in their dwellings, votes in the three central categories of the mTSV scale predominating (FR: 88%, CL: 95%, HT: 88%).

Table 8. Percentage of thermal sensation in each mode

Mode	Items	Modified thermal sensation (mTSV)							Total
		1	2	3	4	5	6	7	
FR	N	115	1,292	4,200	14,248	4,011	1,364	281	25,511
	Percentage (%)	0.5	5.1	16.5	55.9	15.7	5.3	1.1	100
CL	N	7	39	504	4,751	1,265	257	58	6,881
	Percentage (%)	0.1	0.6	7.3	69.0	18.4	3.7	0.8	100
HT	N	62	372	854	2,292	87	5	-	3,672
	Percentage (%)	1.7	10.1	23.3	62.4	2.4	0.1	-	100

N: Number of sample

To locate the thermal comfort zone, Probit regression analysis was conducted for the modified thermal sensation vote (mTSV) categories and the indoor air temperature for FR mode. The analysis method is Ordinal regression using Probit as the link-function and the air temperature as the covariate (Rijal et al. 2017). The results are shown in Table 9.

Technical detail of the calculation:

The temperature corresponding to the median response (Probit = 0) is calculated by dividing the constant by regression coefficient. The inverse of the Probit regression coefficient is the standard deviation of the cumulative Normal distribution. For example, the standard deviation of air temperature of the FR mode will be 1/0.211 = 4.7 °C (Table 9). Transforming the Probits using the following function into proportions gives the curves of Figure 6a–b. The vertical axis is the proportion of votes.

Probability = CDF.NORMAL (quant, mean, S.D.) (7)

where 'CDF.NORMAL' is the Cumulative Distribution Function for the normal distribution, 'quant' is the indoor air temperature (°C); the 'mean' and 'S.D.' are given in the Table 9.

The highest line on figure 6(a) is for category 1 (very cold) and so on successively. Thus, it can be seen that the temperatures for thermal neutrality (a probability of 0.5) is around 24 °C (Figure 6(a)). Reckoning the three central categories as representing thermal comfort, and transforming the Probits into proportions gives the bell-curve of Figure 6(b). The result is remarkable in two respects. The proportion of people comfortable at the optimum is very high, only just less that 100%, and the range over which 80% are comfortable is wide—from around 17 to 30 °C. This is presumably because people in their own dwellings are free to clothe themselves according to the room temperature, without the constraints that are apt to apply at the office.

Table 9. Results of the probit analysis

Equation*	Median	S.D.	N	R^2	S.E.
$P(\le 1)=0.211T_i-1.0$	4.7	4.739	25,177	0.48	0.002
$P(\le 2)=0.211T_i-2.5$	11.8				
$P(\le 3)=0.211T_i-3.8$	18.0				
$P(\le 4)=0.211T_i-6.2$	29.4				
$P(\le 5)=0.211T_i-7.2$	34.1				
$P(\le 6)=0.211T_i-8.2$	38.9				

*: All regression coefficients are significant ($p<0.001$), $P(\le 1)$ is the Probit of proportion of the votes that are 1 and less, $P(\le 2)$ is the Probit of the proportion that are 2 and less, and so on., T_i: Indoor air temperature (°C), S.D.: Standard deviation, N: Number of sample, R^2: Cox and Snell R^2, S.E.: Standard error of the regression coefficient.

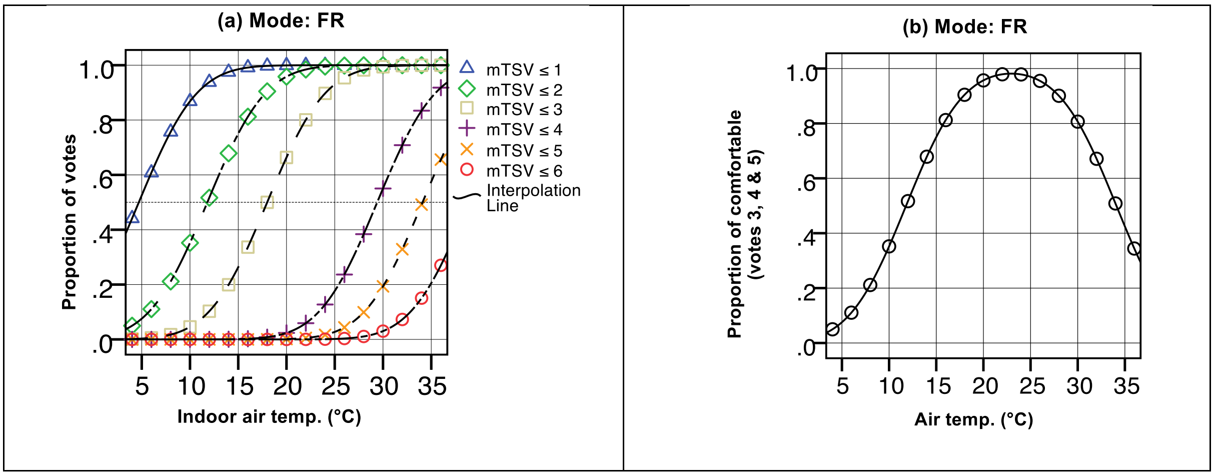


Figure 6. Proportion of modified thermal sensation vote (mTSV) or comfortable (mTSV 3, 4 or 5) for indoor air temperature.

3.4. Estimation of the comfort temperature

Regression analysis of the thermal sensation and indoor air temperature was conducted to estimate the comfort temperature in the three modes (Figure 7). The following regression equations are obtained:

FR mode $mTSV=0.120T_i+1.2$ (n=25,117, R^2=0.47, S.E.=0.001, p<0.001) (8)

CL mode $mTSV=0.098T_i+1.5$ (n＝6,528, R^2=0.08, S.E.=0.004, p<0.001) (9)

HT mode $mTSV=0.081T_i+2.0$ (n=3,582, R^2=0.09, S.E.=0.004, p <0.001) (10)

For example, when the comfort temperature is estimated by substituting '4 neutral' in the equations, it would be 23.3 °C in the FR mode, 25.5 °C in the CL mode and 24.7 °C in the HT mode. The comfort temperature is low in CL mode and high in HT mode compared with the mean temperatures (Table 4). This might be due to the problem of applying the regression method in the presence of adaptive behaviour, where it can lead to depressed regression coefficients with consequent effects on the estimate of the comfort temperature if the mean thermal sensation differs much from neutrality, as has been found in previous research (Rijal et al. 2013). To avoid this problem, in the next section the comfort temperature is estimated using the Griffiths method.

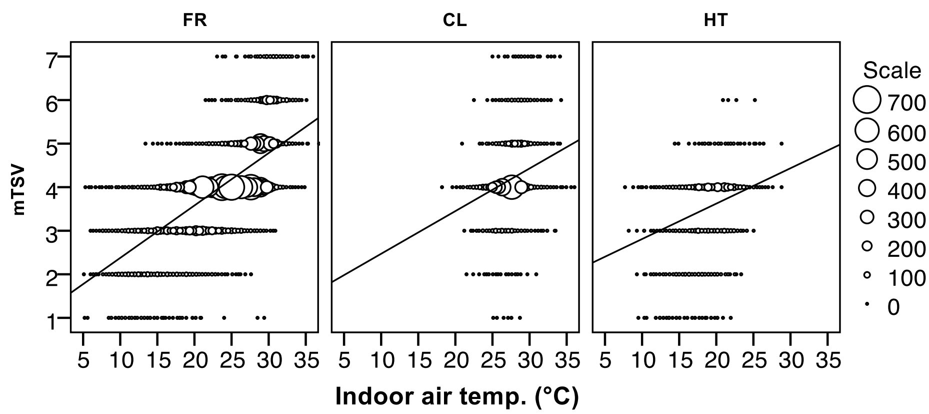


Figure 7. Relation between the modified thermal sensation vote (mTSV) and indoor air temperature.

3.4.1 Griffiths' method

In this section the comfort temperature is estimated by the Griffiths' method (Griffiths 1990, Nicol et al. 1994, Humphreys et al. 2013, Rijal et al. 2013). The method supplies a value for the regression coefficient when, as appears to be the case, the value estimated from the data appears to be misleading. The calculation method is as follows:

$$T_c = T_i + (4 - \text{mTSV}) / a \qquad (11)$$

T_c is comfort temperature by Griffiths' method (°C), T_i is indoor air temperature and 'a' is rate of change of thermal sensation with room temperature, replacing the regression coefficient (Humphreys et al. 2013).

In applying the Griffiths' method, Nicol et al. (1994) and Humphreys et al. (2013) investigated the effect of using various values for 'a' (0.25, 0.33 and 0.50). We have done the same for these data. The mean comfort temperature with each coefficient is similar (Table 10), so it matters little which of these three values is used (bigger differences would have occurred had the value of the coefficient been very low). We choose the value 0.50 for further analysis. These comfort temperatures are also close to the mean temperature when voted '4. Neutral' or '3. No change' (Table 11).

The mean comfort temperatures by the Griffiths' method is 23.6 °C in FR mode, 27.0 °C in CL mode and 19.9 °C in HT mode (Fig. 8). We have calculated the comfort temperature from each thermal sensation vote, and thus the individual differences among the comfort temperatures is high. The correlation between the comfort temperature and indoor air temperature is quite high (Figure 9), showing that fundamentally the people had adapted to a large extent to the temperatures that they had.

Table 10. Comfort temperature estimated by Griffiths' method

Griffiths coefficient	FR			CL			HT		
	N	Mean (°C)	S.D. (°C)	N	Mean (°C)	S.D. (°C)	N	Mean (°C)	S.D. (°C)
0.25	25,177	23.6	3.9	6,528	26.7	2.9	3,582	20.8	3.6
0.33	25,177	23.6	4.0	6,528	26.8	2.4	3,582	20.3	3.2
0.50	25,177	23.6	4.3	6,528	27.0	2.0	3,582	19.9	2.9

N: Number of sample, S.D.: Standard deviation

Table 11. Mean air temperature for '4. Neutral' of mTSV and '3. No change' of TP.

Mode	4. Neutral			3. No change		
	N	Mean (°C)	S.D. (°C)	N	Mean (°C)	S.D. (°C)
FR	14,043	23.9	4.0	14,755	23.7	4.0
CL	4,653	27.1	1.9	4,631	27.1	1.9
HT	2,226	19.4	2.8	2,368	19.3	2.8

N: Number of sample, S.D.: Standard deviation

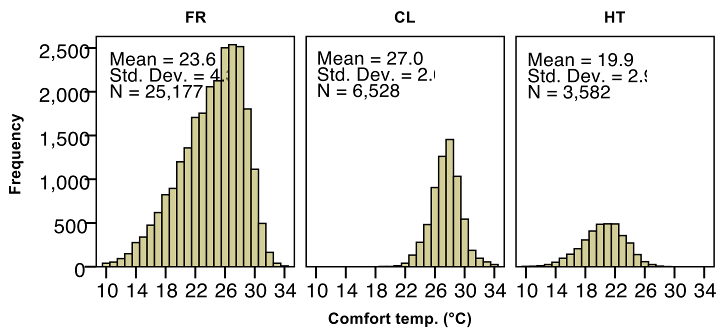


Figure 8. Estimation of comfort temperatures from each observation by Griffiths' method.

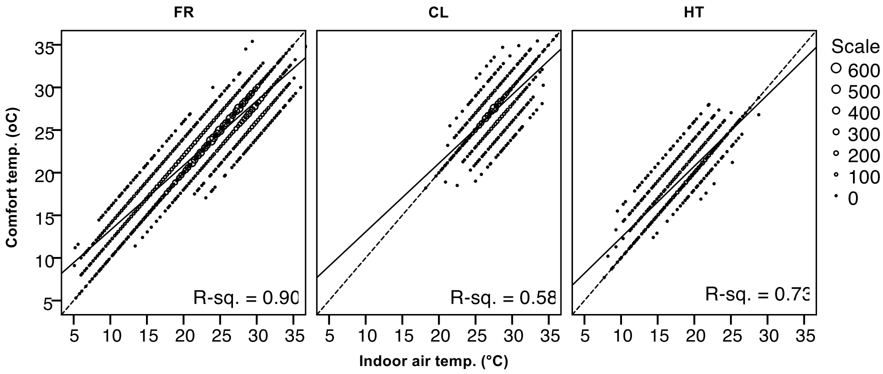


Figure 9. Relation between the comfort temperature and air temperature.

3.4.2 Seasonal difference in comfort temperature

In this section, to clarify the seasonal difference, the comfort temperature for each month and season is investigated (Figures 10 and 11). The results show that the comfort temperature changed according to the season, and thus it is related to the changes in indoor and outdoor air temperature. The comfort temperature by the Griffiths' method is 17.6 °C in winter, 21.6 °C in spring, 27.0 °C in summer and 23.9 °C in autumn in FR mode. Thus, the seasonal difference of the mean comfort temperature is 9.4 K which is similar to the value found in previous research (Rijal et al. 2013). The comfort temperature of the heating HT mode also changes significantly from season to season (Figure 11). The comfort temperature found in previous research ranges from 8.4 to 30.0 °C (Table 12). The wider range may suggest that the comfort temperature has regional differences.

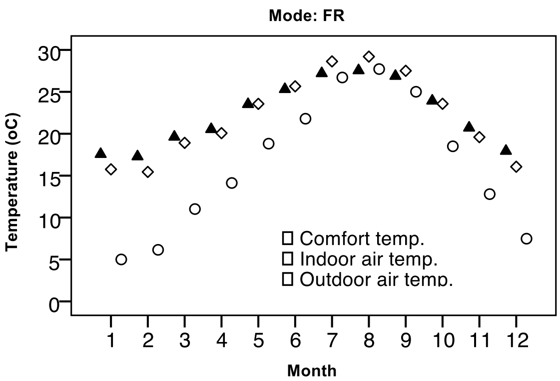


Figure 10. Profiles of the monthly mean comfort temperature, indoor temperature and outdoor temperature with 95% confidence intervals (Mean ± 2 S.E.).

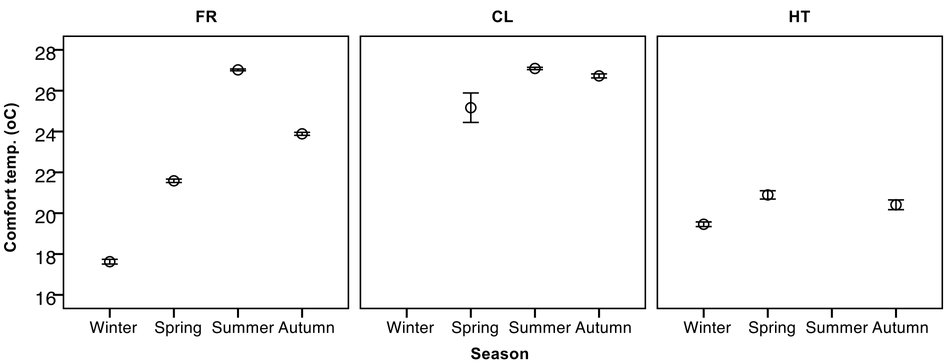


Figure 11. Seasonal variation of comfort temperature with 95 % confidence intervals (Mean ± 2 S.E.).

Table 12. Comparison of comfort temperature with existing research.

Country	Reference	Comfort temperature (°C)			
		Winter	Spring	Summer	Autumn
Japan (Kanto)	This study (FR mode)	17.6	21.6	27.0	23.9
Japan (Gifu)	Rijal et al. (2013)	15.6	20.7	26.1	23.6
Japan (Kansai)	Tobita et al. (2007)	9.9~10.9	-	-	-
Japan (Kansai)	Nakaya et al. (2005)	-	-	27.6	-
Nepal	Rijal et al. (2010)	13.4~24.2	-	21.1~30.0	-
Nepal	Rijal & Yoshida (2006)	8.4~12.9	-	-	-
Pakistan	Nicol & Roaf (1996)	19.8~25.1	-	26.7~29.9	-
UK	Rijal & Stevenson (2010)	19.4	19.7	22.9	21.3

3.5. Towards an adaptive model for Japanese dwellings

3.5.1 Running mean outdoor temperature

The adaptive model requires an index representing the prevailing outdoor temperature. We use T_{rm}, an exponentially weighted daily-mean outdoor temperature. It is calculated using the following equation (McCartney & Nicol 2002).

$$T_{rm} = \alpha T_{rm-1} + (1-\alpha) T_{od-1} \qquad (12)$$

T_{rm-1} is the running mean outdoor temperature for the previous day (°C), T_{od-1} is the daily mean outdoor temperature for that previous day (°C). So, if the running mean has been calculated (or assumed) for one day, then it can be readily calculated for the next day, and so on. α is a constant between the 0 and 1 which defines the speed at which the running mean responds to the outdoor air temperature. In this research α we use the value 0.80, in line with previous findings (see e.g. Humphreys et al. 2013)

3.5.2 Linear regression equations

An adaptive model relates the indoor comfort temperature to the outdoor air temperature (ASHRAE 2004, CEN 2007). Figure 12 shows the relation between the comfort temperature calculated by the Griffiths' method and the running mean outdoor temperature. The regression equations of this study and previous studies are given in Table 13.

The regression coefficient in the FR mode is notably higher than that in the CEN standard. The CEN standard is based on the field investigation in the office buildings, and therefore may not apply to dwellings, where residents have more freedom to adapt. The regression coefficient in the FR mode is close to that found for other Japanese dwellings (Rijal et al. 2013) and to Humphreys (1978) model. However, the regression coefficient in the CL mode or HT mode is notably lower than that in the other Japanese dwellings. These coefficients are higher than in the CIBSE guide (2006). It is interesting to note that the regression coefficient of FR mode is close to the all data.

In the HT mode, the variation of comfort temperature is large. In this research, we have included rooms having a *Kotatsu* (a small table with an electric heater underneath and covered by a quilt) in the HT mode, and thus people may find it comfortable at low indoor air temperatures. When a *Kotatsu* of 90 W (power consumption) is used, there is more than 7 °C thermal comfort effect when room temperature is 11 °C (Watanabe et al. 1997). This may account for the wide range of comfort temperatures found in this research.

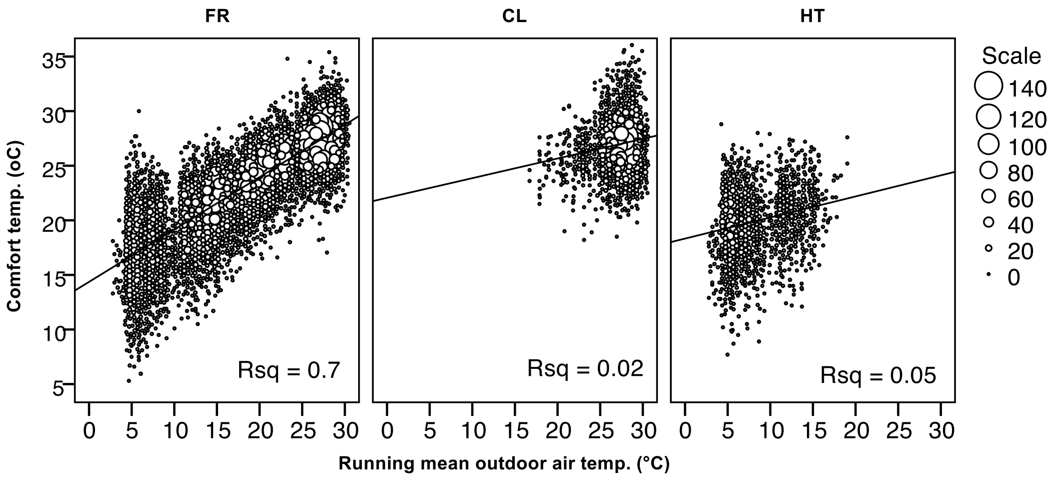


Figure 12. Relation between the comfort temperature and the running mean outdoor temperature.

Table 13. Regression equations in this study and previous studies

References	Buildings	Mode	Equation*	n	R^2	S.E.
This study	Dwellings	FR	T_c=0.480T_{rm}+14.4	25,177	0.70	0.002
		CL	T_c=0.180T_{rm}+22.1	6,528	0.02	0.014
		HT	T_c=0.193T_{rm}+18.3	3,582	0.05	0.014
		All	T_c=0.432T_{rm}+15.4	35,287	0.68	0.002
Rijal et al. (2013)	Dwellings	FR	T_{ci}=0.531T_{rm}+12.5	13,471	0.68	0.003
		CL	T_{ci}=0.297T_{rm}+18.8	1,955	0.06	0.026
		HT	T_{ci}=0.307T_{rm}+16.5	5,240	0.11	0.012
Rijal et al. (2017)	Offices	FR	T_{cg}=0.206T_{rm}+20.8	422	0.42	0.012
		CL&HT	T_{ci}=0.065T_{rm}+23.9	4,236	0.10	0.003
CIBSE (2006)	Offices	CL&HT	T_c=0.09T_{rm}+22.6	-	-	-
CEN (2007)	Offices	FR	T_c=0.33T_{rm}+18.8	-	-	-
ASHRAE (2004)	Offices	NV	T_c=0.31T_{om}+17.8	-	-	-
Humphreys (1978)	All types	FR	T_c=0.534T_{om}+11.9	-	0.97	-

*: Regression coefficient of this research is statistically significant ($p<0.001$), n: Number of sample, R^2: Coefficient of determination, S.E.: Standard error of the regression coefficient (°C), FR: Free running, CL: Cooling, HT: Hearing, NV: Naturally ventilated, T_c: Comfort temp. (°C), T_{ci}: Indoor comfort air temp. (°C), T_{cg}: Indoor comfort globe temp. (°C), T_{rm}: Daily running mean outdoor air temp. (C), T_{om}: Monthly mean outdoor air temp. (°C).

3.5.3 Comparison with other adaptive models

Figure 13 shows the variation of the comfort temperature in the data underlying the CEN standard (Nicol & Humphreys 2007), Japanese dwellings (Rijal et al. 2013) and in this research. When we compare the regression lines of these three figures, it is very similar in the hot environment (about 25~30 °C). In the European research, when outdoor running mean temperature is below 12 °C, the comfort temperature is almost constant (Figure 13 (a)). On the other hand, in the Japanese dwellings, when outdoor running mean temperature is below 12 °C, the comfort temperature is also gradually decreasing. In this research, residents were free to adjust the thermal environment in their home, and thus they might be adapting more in the low outdoor temperature. In the European offices the winter temperature is often governed by a control system rather than set by the occupants.

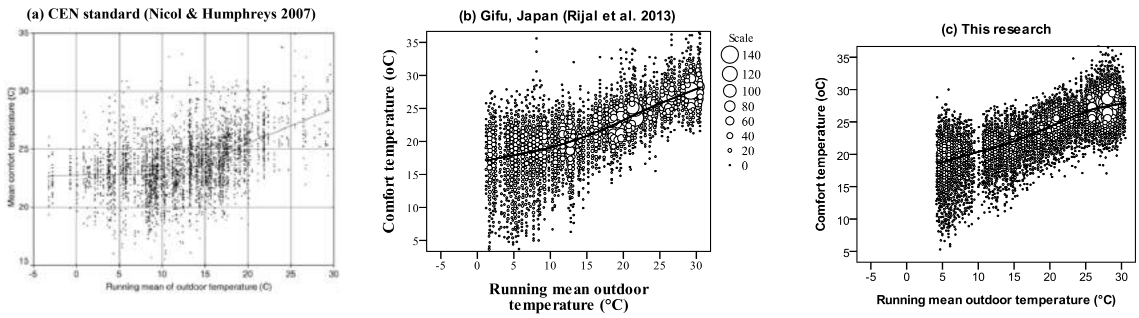


Figure 13. Variation of the comfort temperature in previous and this research.

3.6. Adaptive mechanisms

As we discussed in the previous section, the comfort temperature varies greatly with the outdoor temperature, more than had been found in European offices. The reason might be that the residents are adapting well in their homes using various behavioural, physiological and psychological adaptations. This section focuses on adaptive mechanisms to regulate the thermal environment.

3.6.1 Behavioural adaptations

It is well-known that behavioural adaptations are the most important contributor in the adaptive model. Nicol and Humphreys (2004) made use of logistic analysis to predict occupant control behaviour in naturally ventilated buildings. We have also adopted the logistic regression method here, using SPSS version 23 for the calculations. The following regression equations were obtained in between the behavioural adaptations and the outdoor air temperature.

FR modelogit(P_W)=0.241T_o-5.6 (n＝25,212, R^{2*}=0.35, S.E.=0.003, p<0.001) (13)

FR modelogit(P_F)=0.282T_o-8.3 (n＝24,303, R^{2*}=0.23, S.E.=0.005, p<0.001) (14)

All modelogit(P_C)=0.277T_o-8.1 (n＝34,678, R^{2*}=0.26, S.E.=0.004, p<0.001) (15)

All modelogit(P_H)=-0.233T_o+0.8 (n＝30,566, R^{2*}=0.20, S.E.=0.004, p<0.001) (16)

Where, P_W is the proportion of window opening, P_F is the proportion of fan on, P_C is the proportion of cooling on, P_H is the proportion of heating on and R^{2*} is the Cox and Snell R^2.

We have also analysed the clothing insulation (I_{cl}, clo) and outdoor air temperature, and the following regression equation is obtained.

FR modeI_{cl}=-0.018T_o+0.83 (n＝21,928, R^2=0.33, S.E.=0.0002, p<0.001) (17)

These equations are shown in Figure 14. The adaptive behaviours are highly related to the outdoor air temperature. When the outdoor air temperature decreased, the clothing insulation and the proportion using heating increased. The mean clothing insulation ranges from about 0.20 to 0.80 clo over the range of outdoor air temperature, indicating a large seasonal variation. When outdoor air temperature is below 4°C, about half of the residents use their heating. When the outdoor air temperature increases, the proportion of window opening, fan use and cooling use increase. The proportion of window opening is similar to previous research in Japanese dwellings (Rijal et al. 2013). When outdoor air temperature is 23°C and 29°C, about half of the residents open the window and use the cooling. The results showed that the behavioural adaptations contributed to the adaptive model significantly.

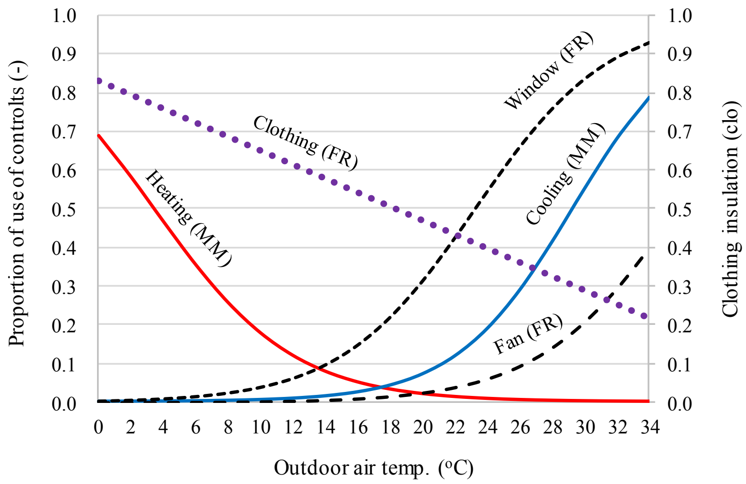


Figure 14. Relation between the adaptive mechanisms and outdoor air temperature.

3.6.2 Physiological adaptation

It is not easy task to quantify the physiological adaptations in the field survey. Here, we will discuss about the skin moisture feeling in summer which might be related to the comfort temperature. Figure 15 shows the relation between the comfort temperature and the indoor air temperature for the four levels of the skin moisture. The regression equation is given below.

$$T_c = 0.825T_i - 1.317SM + 5.8 \quad (18)$$

(n=7868, R^2=0.68, S.E.$_1$=0.006, S.E.$_2$=0.019, p_1 and p_2<0.001)

(SM is skin moisture sensation, S.E.$_1$ and S.E.$_2$ are standard error of regression coefficient for first and second terms, p_1 and p_2 are significance level of the regression coefficients of the first and second terms.)

The equation (18) shows it has a considerable effect on the comfort temperature, an increase of one category in the level of skin moisture reducing the comfort temperature by approximately 1.3 K (Figure 15). Nicol (1974) found that when indoor air temperature is 31–40 °C, increased air speed reduced the assessed skin moisture. Our results therefore imply that the evaporation of the skin moisture is important in raising the comfort temperature in Japan's hot and humid season and consequently contributing to the adaptive model.

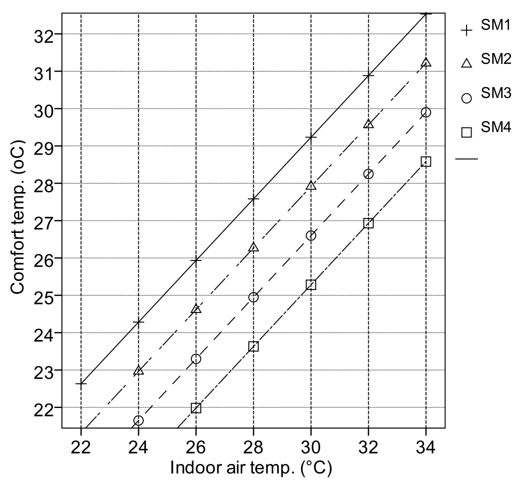


Figure 15. Relation between the comfort temperature and the indoor air temperature for the four levels of skin moisture (Rijal et al. 2015).

3.6.3 Psychological adaptation

Psychological adaptations are not yet well understood. They may include expecting a range of conditions, accepting a range of sensations, enjoying variety of sensation, accepting behavioural adaptations and accepting responsibility for control (Humphreys 2008). We have asked the cognitive temperature (what the respondent thought the temperature was) during the voting, and it may be possible to regard this as a psychological adaptation. Figure 16 shows the relation between the cognitive temperature and measured indoor air temperature. The regression equations are given below.

FR T_{cog}=0.902T_i+1.4 (n=15,189, R^2=0.78, S.E.=0.004, p<0.001) (19)

CL T_{cog}=0.467T_i+14.0 (n=4,734, R^2=0.22, S.E.=0.013, p<0.001) (20)

HT T_{cog}=0.580T_i+7.6 (n=2,714, R^2=0.15, S.E.=0.027, p <0.001) (21)

The regression coefficient and correlation coefficient in the FR mode are much higher than in the CL or HT mode. When the indoor air temperature is high, the cognitive temperatures are lower in all modes than indoor air temperatures, and vice versa for the low indoor air temperature conditions. The results suggest that it was possible to adapt psychologically to high temperatures in summer and low temperature in winter.

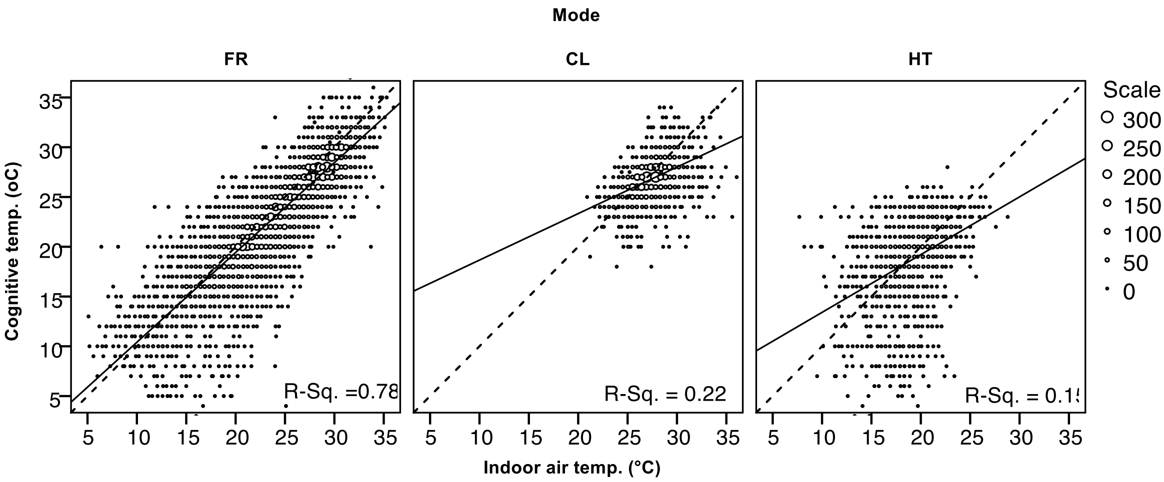


Figure 16 The relation between the cognitive temperature and measured indoor air temperature.

4. Conclusions

A thermal comfort survey of the residents of the Kanto region of Japan was conducted for 4 years. The thermal environment in living rooms and bedrooms were investigated. The following results were found:

1. The residents proved to be generally satisfied with the thermal environment of their dwellings.
2. The comfort temperature in free running mode was about 27 °C in summer and 18 °C in winter, and thus the seasonal difference was high at 9.4 K.
3. An adaptive relation between the comfort temperature indoors and the outdoor air temperature could be a useful way to estimate the comfort temperature and for informing control strategies.
4. People used the various adaptive mechanisms to regulate the thermal environment which support the adaptive model.

Acknowledgements

We would like to thank the households who participated in the survey and the students for data entry. This research was supported by Grant-in-Aid for Scientific Research (C) Number 17K06681.

5. References

ASHRAE Standard 55 (2004). Thermal environment conditions for human occupancy. Atlanta, Georgia, American Society of Heating Refrigeration and Air-conditioning Engineers.

CIBSE (2006), Environmental Design. CIBSE Guide A, Chapter 1, Environmental criteria for design. London: Chartered Institution of Building Services Engineers.

Comité Européen de Normalisation (CEN) (2007). EN 15251: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics. CEN, Brussels.

Griffiths, I.D., 1990. Thermal comfort in buildings with passive solar features: Field studies. Report to the Commission of the European Communities. EN3S-090 UK: University of Surrey Guildford.

Humphreys M.A. (1978), Outdoor temperatures and comfort indoors, Building Research and Practice (Journal of CIB), 6(2): 92-105.

Humphreys M.A., Nicol J.F. (1998), Understanding the Adaptive Approach to Thermal Comfort, ASHRAE Transactions 104(1): 991-1004.

Humphreys, M.A. (2008), Adaptive thermal comfort in buildings, International Exchange Committee of the Kinki Branch of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, 17 October, Kyoto, Japan.

Humphreys, M.A., Rijal, H.B. and Nicol, J.F., 2013. Updating the adaptive relation between climate and comfort indoors: new insights and an extended database. Building and Environment, 63, pp. 40-55.

McCartney K.J., Nicol J.F. (2002), Developing an adaptive control algorithm for Europe, Energy and Buildings, 34 (6): 623-635.

McIntyre, D.A., (1980). Indoor climate. London: Applied Science Publishers, Ltd.

Nakaya T., Matsubara N., Kurazumi Y. (2005), A field study of thermal environment and thermal comfort in Kansai region, Japan: Neutral temperature and acceptable range in summer, J. Environ. Eng., AIJ, No.597: 51-56.

Nicol, J.F. (1974), An analysis of some observations of thermal comfort in Roorkee, India and Baghdad, Iraq. Ann. Hum. Biol., 1, 411–426.

Nicol, F., Jamy, G.N., Sykes, O., Humphreys, M., Roaf, S. and Hancock, M., 1994. A survey of thermal comfort in Pakistan toward new indoor temperature standards. Oxford Brookes University, Oxford England.

Nicol, F. and Roaf, S., 1996. Pioneering new indoor temperature standards: the Pakistan project. Energy and Buildings, 23, pp. 169-174.

Nicol J.F., Humphreys M.A. (2004), A stochastic approach to thermal comfort – occupant behavior and energy use in buildings. ASHRAE Transactions, 110(2): 554-568.

Nicol J.F., Humphreys M.A. (2007), Maximum temperatures in European office buildings to avoid heat discomfort, Solar Energy 81 (3): 295-304.

Oseland N.A. (1995), Predicted and reported thermal sensation in climate chambers, offices and homes. Energy and Buildings, 23(2): 105-115.

Rijal H.B., Tuohy P., Humphreys M.A., Nicol J.F., Samuel A., Raja I.A., Clarke J. (2008), Development of adaptive algorithms for the operation of windows, fans and doors to predict thermal comfort and energy use in Pakistani buildings. ASHRAE Transactions, 114 (2): 555-573.

Rijal H.B., Stevenson F. (2010), Thermal comfort in UK housing to avoid overheating: lessons from a 'Zero Carbon' case study, Proceedings of Conference: Adapting to change: New thinking on comfort, Windsor, UK, 9-11 April 2010. London: Network for Comfort and Energy Use in Buildings.

Rijal H.B., Yoshida H. (2006), Winter thermal comfort of residents in the Himalaya region of Nepal, Proceedings of International Conference on Comfort and Energy Use in Buildings - Getting them Right (Windsor), Organised by the Network for Comfort and Energy Use in Buildings.

Rijal H.B., Yoshida H., Umemiya N. (2010), Seasonal and regional differences in neutral temperatures in Nepalese traditional vernacular houses, Building and Environment, 45(12): 2743-2753.

Rijal, H.B., Honjo, M., Kobayashi, R. and Nakaya, T., 2013. Investigation of comfort temperature, adaptive model and the window opening behaviour in Japanese houses. Architectural Science Review, 56(1), pp. 54-69.

Rijal, H.B., Humphreys, M.A., Nicol, J.F., 2014, Development of the adaptive model for thermal comfort in Japanese houses, Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a changing world, Cumberland Lodge, Windsor, UK, 10-13 April 2014. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Rijal, H.B., Humphreys, M. and Nicol, F., 2015, Adaptive thermal comfort in Japanese houses during the summer season: Behavioral adaptation and the effect of humidity, Buildings 5(3), pp. 1037-1054.

Rijal, H.B., Humphreys, M.A. and Nicol, J.F., 2015. Comfortable indoor temperatures and the climate: An adaptive model for Japanese dwellings, The International Joint-Conference Senvar-Inta-Avan 2015, 24-26 November, Wisdom of The Tropics: Past Present & Future, No. 1, pp. 100-109.

Rijal, H.B., Humphreys, M.A. and Nicol, J.F., 2017. Towards an adaptive model for thermal comfort in Japanese offices, Building Research & Information 45(7), pp. 717–729.

Tobita K., Nakaya T., Matsubara N., Kurazumi Y., Shimada R. (2007), Calculation of neutral temperature and acceptable range by the field study of houses in Kansai area, Japan, in winter, J. Environ. Eng., AIJ, No. 614: 71-77.

Watanabe S., Horikoshi T., Miyoshi Y., Miyamoto S. (1997), Thermal effect of heating lower extremities of the human body using Kotatsu on the human thermal comfort, J. Archit. Plann. Environ. Eng., AIJ, No. 497: 47-52.

Thermal Comfort for Occupants of Nursing Homes: A Field Study

Federico Tartarini[1], Paul Cooper[1] and Richard Fleming[2]

[1] Sustainable Buildings Research Centre (SBRC), University of Wollongong, Innovation Campus, North Wollongong, NSW 2522, Australia, sbrc@uow.edu.au;
[2] Faculty of Science, Medicine and Health, University of Wollongong, Wollongong, NSW, Australia.

Abstract: The primary aim of this research was to assess the quality of the thermal environment of six Australian nursing homes, and to understand and quantify the impacts of the indoor thermal environment on the perceptions and comfort of staff, residents and other occupants. The impact of the thermal environment on perceptions and comfort of building occupants of six nursing homes was determined through: 1) a long-term building evaluation survey (staff members only); and 2) a point-in-time thermal comfort study, involving 322 residents and 187 non-residents. In addition, a combination of spot-measurements and long-term monitoring of indoor air temperatures was used to assess the overall quality of the thermal environment in the nursing homes. Results showed that some facilities did not provide a thermally comfortable environment for occupants through both summer and winter seasons, while results from the point-in-time study showed that residents preferred warmer temperatures (0.9°C) and generally wore more clothes than non-residents. The article also presents a discussion of the applicability of adaptive thermal comfort approaches to assessment of the indoor environment in nursing homes and differences between the perceptions/preferences of residents versus staff.

Keywords: Thermal comfort, nursing homes, aged care facilities, field study, older adults.

1. Introduction

The proportion of older people in the global population is currently at its highest in human history (UN, 2013). The trend towards populations having increasingly higher proportions of older people is widespread across all nations and is certainly the case in Australia (AIHW, 2017a). As a consequence, the need for nursing home care is projected to rise markedly (ACFA, 2016). In 2014-15, in Australia, there were 2,681 residential aged care homes providing 192,370 operational aged care places (ACFA, 2016). Nursing homes (also called residential aged care homes or hostels for the aged) are special-purpose facilities with a domestic-style environment that provide accommodation and 24-hour support to frail and aged residents. Nursing homes in Australia provide care to those who have dementia and are neither hospitals nor psychiatric facilities (AIHW, 2017b).

In Australia, the Australian Aged Care Quality Agency is the supervisory authority which is responsible for ensuring that aged care facilities provide high standards of care to residents (DSS, 2014). However, the current accreditation standards do not set minimum temperature thresholds (for health and thermal comfort) for nursing homes and for spaces occupied by older people (AACQA, 2011). As a result, there is the potential for residents of aged care facilities to be exposed to environmental conditions, which may negatively influence their health (Gupta et al, 2017; OEH, 2014), and affect the behaviours of residents with dementia (Tartarini et al, 2017).

Furthermore, there appears to be a lack of consensus on how the indoor environment is perceived by older adults generally (those aged 65 years or older) and the two main international thermal comfort standards, i.e. ASHRAE 55-2013, ISO 7730:2005, are only applicable to healthy adults (ASHRAE, 2013; ISO, 2005). Consequently, there is very limited guidance and recommendations available worldwide to help building designers and aged care providers to understand how to properly regulate indoor environmental quality (IEQ) in nursing homes.

Nursing homes represent a hybrid category of buildings, and each facility is generally made up of a mix of residential, offices and commercial spaces. The task of providing a comfortable thermal environment in such buildings is complicated by the fact that they house two distinct groups of occupants, i.e. residents and non-residents, which have different thermal requirements and needs. Residents spend the majority (80% to 90%) of their time indoors (Mendes et al, 2015) and many of them depend on their environment to compensate for the physical and cognitive frailties associated with their conditions (Marquardt and Schmieg, 2009; Wong et al, 2014). On the other hand, caregivers are often involved in physically demanding tasks.

The aim of this field study was to assess the quality of the thermal environment in a sample of Australian nursing homes, and to understand and quantify the impacts of thermal environment on perceptions and comfort of occupants.

2. Case Study Facilities

The research was carried out in six accredited nursing homes. All facilities were located in south-eastern NSW, however, they were situated in areas with a range of diverse climates. The elevation and climatic zone of each nursing home are listed in Table 1, while the key features of each home are presented in Table 2.

Table 1. Climatic zones and elevation above sea level of each nursing home (NH).

Location	Elevation (m)	Climatic zone	
		Australian National Construction Code	Köppen–Geiger
NH 1	9	5	Cfa
NH 2	670	6	Cfb
NH 3	43	5	Cfa
NH 4	643	7	Cfb
NH 5	77	5	Cfa
NH 6	3	5	Cfa

3. Research Method

The field study was divided in three main activities:

- long-term monitoring of indoor air temperatures;
- a long-term building evaluation survey; and
- a point-in-time thermal comfort study.

All the research activities were approved by the University of Wollongong Human Research Ethics Committee (approvals HE14/478 and HE15/235).

3.1. Long-term Monitoring of Indoor Air Temperature

Stand-alone iButton™ sensors/data loggers were used to measure dry-bulb air temperature. The data loggers were cylindrical in shape (17.5 mm in diameter and 6 mm deep) and according to the manufacturer's specification they measured temperature with an accuracy and resolution of ±0.5°C which, therefore, met the accuracy requirements of ISO 7726:1998 standard (ISO, 1998).

Table 2. Key features of the case study facilities. Air Conditioning (AC).

Home	N of beds (dementia section)	Floor area - m^2 / resident	Building features							
			Construction date	External walls	Lighting	Windows	Ceiling	Bedrooms		Common areas
								Heating	Cooling	
NH 1	150 (13)	$7040m^2$ – $46.9m^2$/res	1993; partially renovated in 1997 and 2008	Double-brick no insulation	Incandescent, compact and tubular fluorescent lamps	Single glazed, metallic frame	Partial ceiling insulation	Electric convection and hydronic radiators, split A/C	Few rooms had split A/C	Ducted, split and cassette A/C
NH 2	90 (25)	$5410m^2$ – $60m^2$/res	2007	Double-brick no insulation	Compact and tubular fluorescent lamps	Single glazed, metallic frame	Insulated	Split A/C	Split A/C	Ducted A/C
NH 3	62 (14)	$1651m^2$ – $26.6m^2$/res	1955	Double-brick no insulation	Incandescent, compact and tubular fluorescent lamps	Single glazed, metallic frame	Unknown	Ducted/gas heater	No	Split or cassette A/C
NH 4	160 (25)	$6570m^2$ – $41.1m^2$/res	2008	Double-brick no insulation	Compact and tubular fluorescent lamps	Single glazed, metallic frame	Insulated	Split A/C	Split A/C	Ducted A/C
NH 5	40 (0)	$1945m^2$ – $48.6m^2$/res	1968; in 1985 were added 40 beds	Double-brick no insulation	Incandescent, compact and tubular fluorescent lamps	Single glazed, metallic frame	Unknown	Electric convection radiators and hydronic radiators	No	Split A/C dining room
NH 6	101 (55)	$3271m^2$ – $32.4m^2$/res	1984	Double-brick no insulation	Incandescent, compact and tubular fluorescent lamps	Single glazed, metallic frame	Partial ceiling insulation	Hydronic radiators	No	Split A/C dining room, cassette A/C installed 2/2016

The sensors recorded data at hourly intervals from 1st September 2015 to 11th of January 2017. The sample rate of once per hour was constrained by the limited on-board sensor memory and the need to provide a sufficiently long duration between visits by the researcher to each facility. The specific elevation of each sensor was selected according to the most common type of activity and body position of occupants at a given location (0.6 m when sitting/reclining, 1.1 m standing) as suggested in ISO 7726:1998. Sensors were installed on internal walls next to where occupants spent the majority of their time indoors. They were neither exposed to solar radiation nor to direct radiation/convection from neighbouring heat sources. Temperature data collected when rooms were unoccupied were not included in the analysis, and occupancy profiles for the various indoor areas studied are presented in Table 3.

Table 3. Occupancy profiles assumed for the case study facilities by room type.

Type of room	Occupancy profiles
Bedroom, Toilet and Shower, Corridor, nurses station, Staff Dining Room, Corridor	24 hours
Dining Room, Lounge, Sitting Room	Between 5.00 AM and 11.00 PM
Physiotherapy Room, Therapy Room, Laundry, Office, Treatment Room, Reception	Between 7.00 AM and 6.00 PM
Kitchen	Between 5.00 AM and 8.00 PM
Activities Room	Between 9.00 AM and 6.00 PM

When analysing the temperature dataset the lower and the upper limits of the comfort temperature range were taken to be 20°C and 26°C, respectively. This range was selected following the recommendations provided in Annex A of the ISO 7730:2005. Guidelines from ISO 7730:2005 were used since, at the time of writing, the Australian residential aged care Accreditation Standards did not provide guidelines in regards to a temperature range to be maintained in nursing homes. Furthermore, the World Health Organization suggests that a minimum air temperature of at least 20°C be maintained in indoor environments for people with special requirements, to avoid the possibility of their body temperature decreasing, potentially leading to hypothermia or other issues (WHO and UNEP, 1990).

For this phase of the research, air velocity and mean radiant temperature were not recorded during the long-term monitoring, since this would have required significant additional financial expenditure. This approach aligns with advice in ASHRAE 55-2013, which states (page 45) that "Measuring indoor air movement in long-term studies is very difficult and rarely done. In many indoor situations the indoor airspeed conforms to the still air conditions of the PMV comfort zone (0.2 m/s [40 fpm]), in which case, air speed measurement is not necessary".

In addition, the decision was taken not to measure mean radiant temperature since values of mean radiant temperature are used solely to estimate operative temperature, however, operative temperature can only be determined if air velocity values are known.

3.2. Long-term Building Evaluation Survey

Several types of long-term evaluation surveys, also known as post occupancy evaluation surveys, have been previously developed by other researchers to assess the correlation between IEQ factors and occupant satisfaction with the indoor environment (Peretti and Schiavon, 2011). However, the majority of these tools comprise questions that are not relevant in nursing home settings, and limited benchmark data is available regarding performance of nursing homes.

Thus, a bespoke survey was developed by the present authors to assess the IEQ performance of nursing homes. This was implemented as an on-line resource so as to recruit as many responses as possible across the wide geographic locations of the facilities, differing staff working hours, etc. The framework and the great majority of the questions contained in the building survey were developed using the Occupant Indoor Environmental Quality (IEQ) Survey™ developed by the Center for the Built Environment, University of California Berkeley (CBE, 2014) for residential and healthcare buildings and the long-term evaluation survey provided in Appendix K of ASHRAE 55-2013 standard (ASHRAE, 2013).

The questionnaire was sent to all employees working in the six facilities and was used to assess how different facilities/buildings performed during winter 2016 and summer 2015/2016. Data collected on thermal comfort were correlated with the temperature data logged.

The questionnaire comprised more than fifty questions, however, in this article only answers to questions related to thermal comfort are presented. Participants were asked to rate their perception of indoor air temperature over the winter and summer periods (separate questions) using the following scale: -3 'cold,' -2 'cool,' -1 'slightly cool,' 0 'neutral,' +1 'slightly warm,' +2 'warm,' +3 'hot.' Similarly, satisfaction with the thermal environment in summer and winter was assessed by asking participants how satisfied they were with the indoor air temperature using a 7-point scale ranging from 'very dissatisfied' to 'very satisfied.'

3.3. Point-in-time Survey

The target population for this research activity was all occupants of nursing homes (staff members, residents and visitors) since a well-designed nursing home should provide comfortable thermal conditions for all occupants. Residents with dementia were invited to participate in the research only if they were judged to have sufficient cognitive abilities to complete the questionnaire.

The point-in-time survey was administered indoors between 9.00 a.m. and 5.00 p.m. over two separate periods of time at each facility. Data representative of the warm season was collected between November 2015 and February 2016, while data representative of the cold season was collected between March 2016 and July 2016. Each participant completed the questionnaire only once per season. Participants were asked to complete a paper-based copy of the questionnaire after the IEQ-monitoring equipment (IEQ Cart) was brought into the room and placed within a 1-meter radius of the participant for 12 minutes. The delay of nominally 12 minutes was chosen to ensure that all sensors had reached thermal equilibrium with the indoor environment. A detailed description of the IEQ monitoring Cart is provided in Tartarini et al. (2017).

The questionnaire was used to collect both the physical characteristics of participants (e.g. age, height, weight) and to assess their perceptions of the thermal environment using the ASHRAE seven-point thermal sensation scale subdivided as follows: -3 'cold,' -2 'cool,' -1 'slightly cool,' 0 'neutral,' +1 'slightly warm,' +2 'warm,' and +3 'hot' (ASHRAE, 2013).

Clothing insulation and activity levels were assessed through observation by the first author and by asking participants to list the garments that they were wearing. Activity level was selected using the tables provided in ISO 7730:2005 and ASHRAE 55-2013 Standards.

Assessment of Indoor Environmental Parameters

While participants were completing the point-in-time questionnaire, the following environmental parameters were measured and recorded: indoor air temperature T_a (°C), globe temperature T_g (°C), air velocity V_a (m/s), and relative humidity RH (%). The average indoor air temperature ($\overline{T}_a$), average globe temperature ($\overline{T}_g$) and average air velocity ($\overline{V}_a$) for each resident were calculated based on the body position of occupants as specified in ISO 7730:2005 Standard. All sensors were calibrated prior to data collection according to manufacturers' instructions.

Data Analysis

For each participant the following indices were also calculated: total clothing insulation (I_{clo}), operative temperature (T_o), mean radiant temperature (T_{mrt}), metabolic rate (M), Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). Data analysis was carried out using the IBM SPSS Statistics software (V21, IBM Corporation, Armonk, NY) and MATLAB (R2016b).

Total clothing insulation (I_{clo}) was determined using the methodology and the tables provided in ISO 7730:2005 (ISO, 2005) and ASHRAE 55-2013 (ASHRAE, 2013) standards. However, because these standards cannot be used to determine I_{clo} of people in bed, their I_{clo} was determined by coupling the data collected (i.e. body position, sleepwear, and bedding) with the most similar combination of beds, bedding and sleepwear provided in Lin and Deng (2008).

The mean radiant temperature was calculated using the equations provided in Annex B and Annex G of ISO 7726 standard (ISO, 1998). While the Predicted Mean Vote (PMV) was evaluated using the computer program provided in Appendix B of ASHRAE 55-2013 (ASHRAE, 2013).

4. Results and Discussion

4.1. Long-term Monitoring of the Indoor Air Temperature and Relative Humidity

The outdoor and indoor temperatures from all the sensors installed in the case study facilities are presented in Figure 1. NH 2 and NH 4 were located in climatic zones with relatively cold winters (by Australian standards), the minimum temperature in winter being below 0°C. The remaining facilities were closer to the coast, hence ambient temperature variations throughout the year were mitigated, to some extent, by their proximity to the ocean.

In NH 2 and 4 all rooms were service by air conditioning systems and the indoor temperature was maintained relatively constant throughout the year. Whereas, in those rooms in the other facilities which were not serviced by air conditioning systems the indoor temperature varied significantly as a function of the outdoor conditions. For example, Figure 1 shows that during summer the median indoor air temperature in NH 5 was significantly higher than the outdoor temperature and exceeded the threshold of 26°C for more than 62% of the time in February. Furthermore, despite the fact that the median outdoor temperature in winter was approximately 15°C, indoor temperatures below 20°C were recorded for approximately 26% of the time in August. Similar indoor temperature profiles also occurred in NH 3 and NH 6. The main causes of such significant temperature variations in the older facilities were thought to be: the relatively poor thermal performance of the building envelope (e.g. wall, windows, floor and ceiling/roof); the absence of air conditioning systems in some areas; and the absence of an adequate air conditioning control system (including the lack of local control of heating to individual rooms).

It was found that occupants actively influenced indoor air temperatures through their control of openable windows. For example, during warmer weather occupants sometimes opened windows to ventilate the building with outdoor air, however, on some occasions this practice led to indoor overheating when outdoor temperatures were high.

Indoor Air Temperature in the Bedrooms

The indoor air temperature data measured in bedrooms is presented in Figure 2. Despite the fact that in all nursing homes the mean maximum temperature in the bedrooms exceeded 26°C, in NH2 and NH4, where all the bedrooms were equipped with direct expansion air conditioners, temperatures above 26°C occurred for less than 4% of the summer period. Whereas, bedrooms of NH 3, NH 5 and NH 6 were not air conditioned and temperatures above 26°C were recorded for a significantly higher fraction of time. For example, in NH 5 indoor air temperatures exceeded 26°C for approximately 49% of the summer period. By contrast, in NH 2 and 4 the indoor temperatures remained almost constant across the two seasons.

Figure 2 also shows that in NH 2, the mean temperature in the bedrooms in winter was 21.6°C and in summer 22°C; suggesting that the set-point temperatures of the Heating, Ventilation, and Air Conditioning (HVAC) units were maintained at a constant, or close to constant, value with minimal variation between seasons. Evidence from previous studies has shown that metabolism and cardiovascular parameters may be positively influenced by exposure to slightly cool and warm environments (van Marken Lichtenbelt et al, 2017). van Marken Lichtenbelt observed that Type 2 diabetes patients, for example, experienced increased insulin sensitivity of more than 40% after ten days of intermittent exposure to mild cold. Hence, allowing air temperatures to vary slightly indoors may have a positive impact on the health of residents of nursing homes.

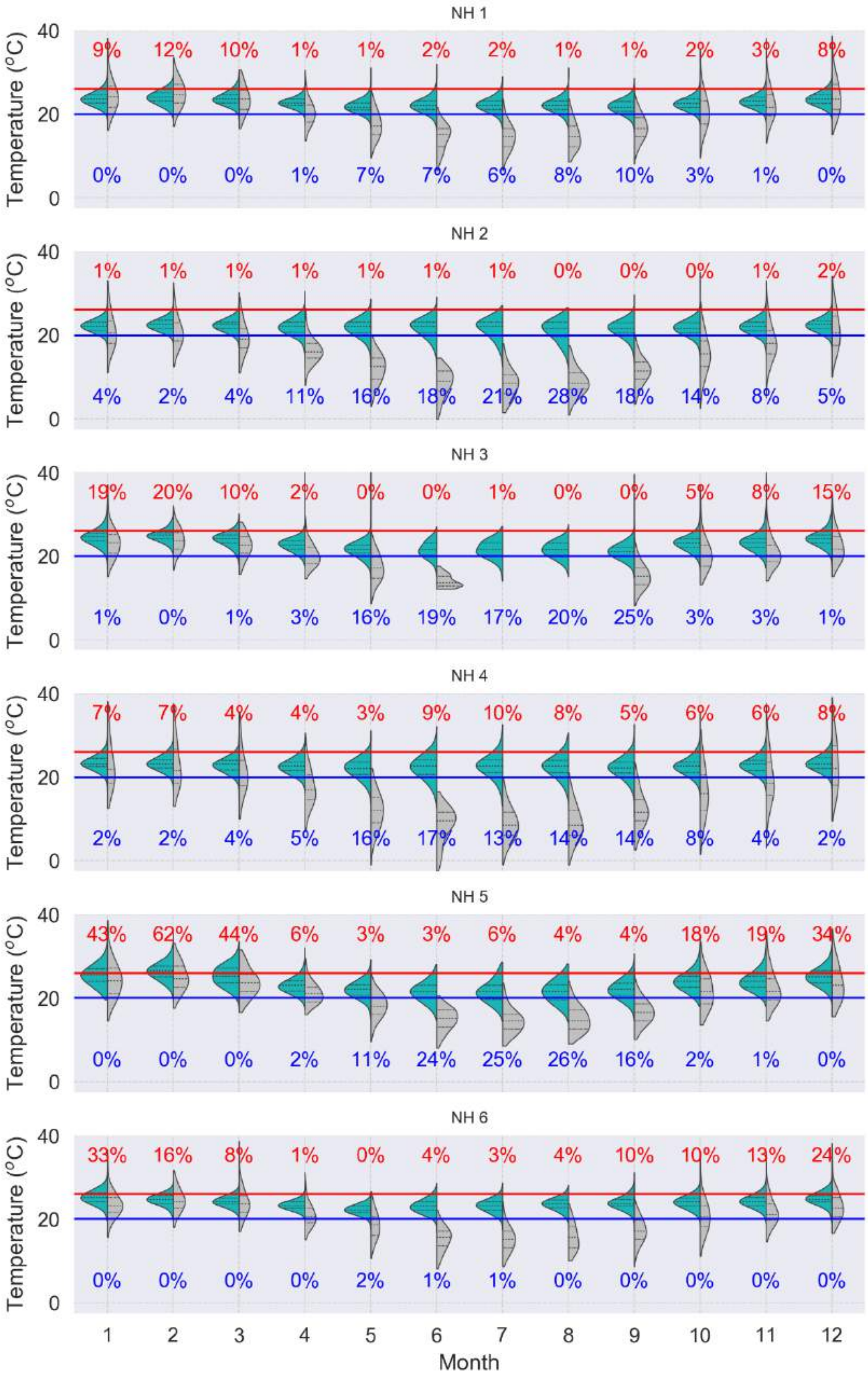


Figure 1. 'Violin Plot' of outdoor (grey) and indoor (turquoise) temperatures at the 6 case study facilities and the percentage of time indoor air temperatures were recorded above 26°C (red) and below 20°C (blue). The width of each side of the 'violin' is proportional to the number of samples, and the horizontal lines inside each 'violin' show the quartiles for each sub set of data.

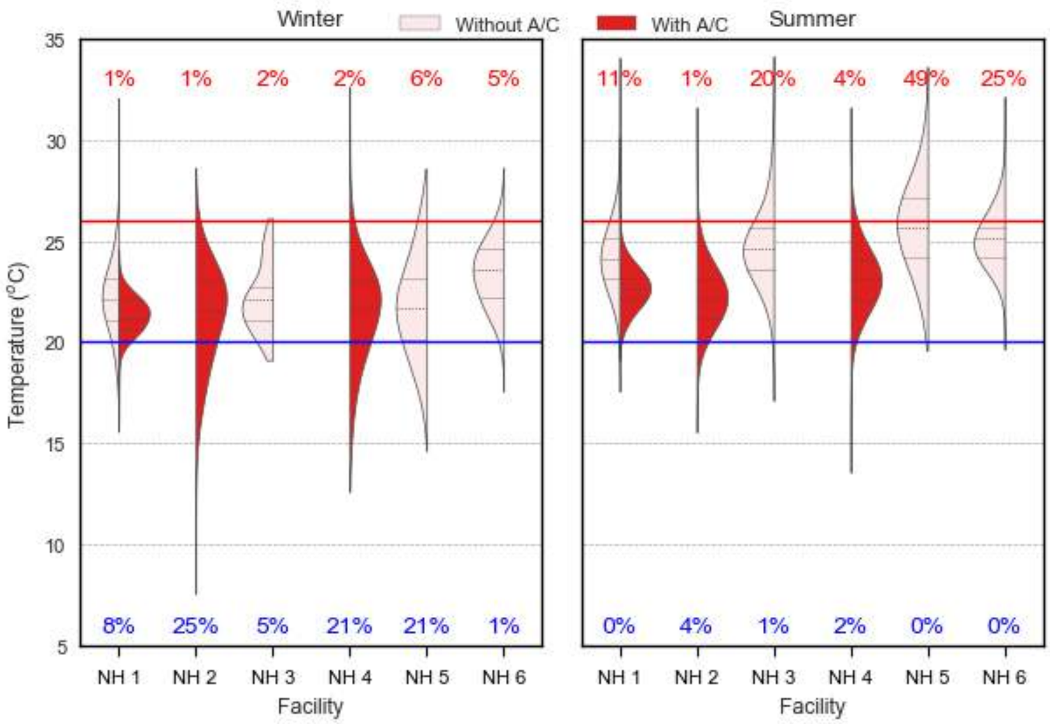


Figure 2. Indoor air temperature data measured in the bedrooms of the six case study facilities in summer (1/12/2015-29/2/2016) and winter (1/06/2016-31/8/2016). The dataset was split between air conditioned bedrooms (light-red) and non-air conditioned bedrooms (red). Also shown are the percentages of time at which indoor air temperatures above 26°C (red) and below 20°C (blue) were recorded.

In NH 5 and NH 6 air temperatures lower than 20°C where observed for more than 20% time during winter. Three factors were thought to be the main causes of such low temperatures: 1) when rooms were unoccupied, cleaners tended to leave the windows open to ventilate the space; 2) occupants preferred temperatures lower than 20°C at night-time; 3) residents did not know how to properly control the heating systems in their rooms. The latter issue could have significant implications for the health of residents. It was observed that in more than one room residents felt cold in the early morning and attempted to warm up their room quickly by turning on the heating and selecting a high set-point temperature. However, it was then observed that around lunch time the rooms were often overheated (e.g. in one bedroom in winter the indoor air temperature was higher than 25°C for approximately 50% of the time) and it appeared that occupants turned off the heating manually, instead of decreasing the set-point temperature of the unit, and consequently the room temperature decreased significantly overnight.

The set-point temperature of hand-held remote controllers installed in the bedrooms, could range from 16°C to 28°C, and residents may have had difficulties in using remotes which had a display with low contrast and buttons which were not clearly marked. Thus, allowing residents, particularly those with dementia, to manually control split air conditioners is unlikely to be the optimal solution when endeavouring to enhance thermal comfort conditions in nursing homes.

Indoor Air Temperature in Dining Rooms

Figure 3 shows the temperature data recorded in the dining rooms, which were all equipped with heating/cooling systems. Air conditioners appeared to have been of sufficient capacity to offset summer thermal loads, as a result there were a relatively small number of hours when temperatures above 26°C occurred.

Mean temperatures were not consistent across the nursing homes during a given season. For example, the median indoor air temperature at NH 2 was 2.1°C lower than at NH 6, which could possibly have been due to differences between the set-points programmed at each facility. Furthermore, in NH 4 (a fully air-conditioned facility) the median indoor air temperature was lower in summer (23.1 °C) than in winter (23.6 °C) due to a low set-point programmed at the facility in summer.

Occupants of NH 4 and NH 2 may have had to compensate for cool indoor air temperatures in summer by wearing extra clothes. Maintaining low air temperatures in summer not only significantly increases the energy consumption of the HVAC units but may also worsen the thermal comfort conditions, especially for those residents who have low metabolic rates.

It was also observed that in several areas of the nursing homes, which were occupied only during office hours and were locked at night-time, the air conditioning system was neither switched off at night-time nor when the rooms were unoccupied.

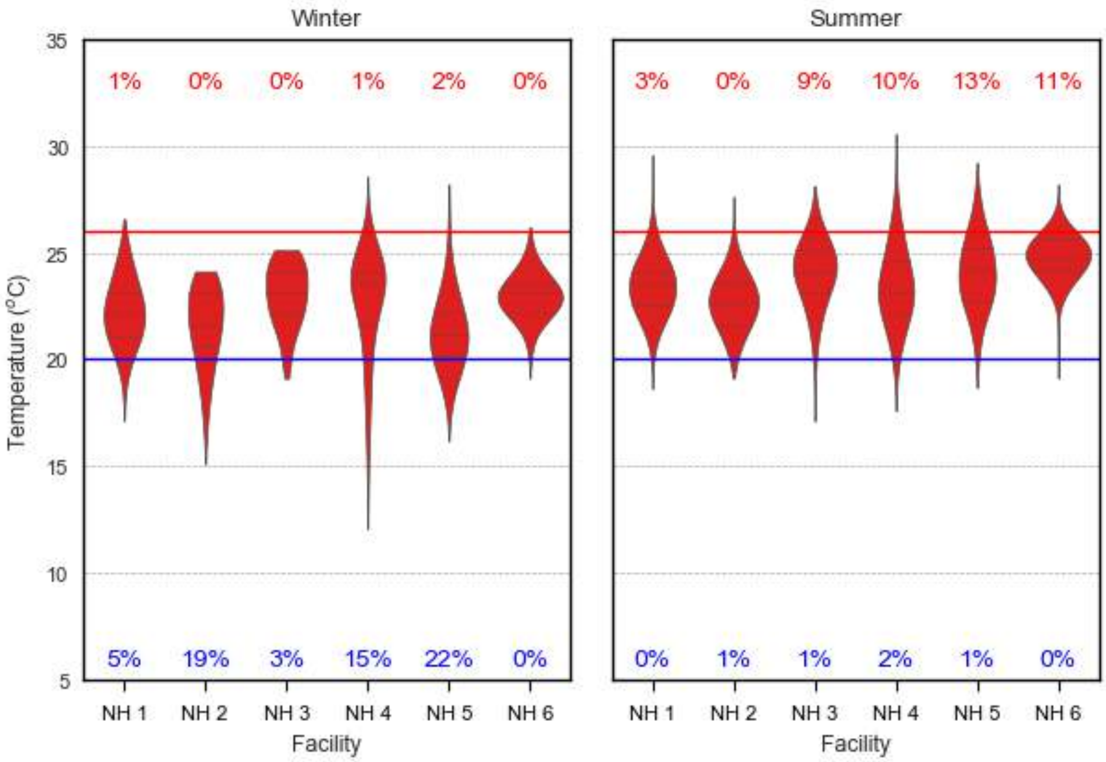


Figure 3. Indoor air temperature data measured in the dining rooms of the six case study facilities in summer (1/12/2015-29/2/2016) and winter (1/06/2016-31/8/2016). All the spaces were air-conditioned.

Comparison with the Adaptive Thermal Comfort Model

The experimental data collected in all the indoor spaces that were not equipped with air conditioning units are plotted versus the prevailing mean outdoor temperature in Figure 4, in order to compare the measured data with the 80% acceptability limits of the Adaptive Thermal Comfort zone as defined by ASHRAE 55-2013. The figure shows that the great majority of the temperature data recorded were within the comfort zone. Also of note was the fact that indoor air temperatures colder than those recommended by the Adaptive Thermal Comfort model were recorded for a higher percentage of time than temperatures above the comfort zone.

It is also important to highlight the fact that the metabolic rates of many residents who were using these spaces were lower than the range specified by the Adaptive Thermal

Comfort model (1.0 – 1.3 met). Therefore, this may even imply that the lower boundary of the Adaptive Thermal Comfort zone could be r to compensate for low metabolic rates of occupants in nursing homes.

Furthermore, some areas of the older facility were serviced by air conditioning systems. Hence, occupants may have spent part of their day in air-conditioned spaces and the remaining part in spaces that did not have mechanical cooling/heating. Figure 5 shows the temperature profiles of three rooms that were located in close proximity to each other in NH 6. Both the dining room and the reception were equipped with mechanical cooling, whilst the bedroom was not. In January 2016, for approximately 26% of the time the temperature difference between the bedroom and the reception was greater than 6°C, consequently occupants were likely to have felt uncomfortable as they moved from one room to another. Staff attempted to mitigate this problem by cross ventilating the spaces using pedestal fans in the corridor.

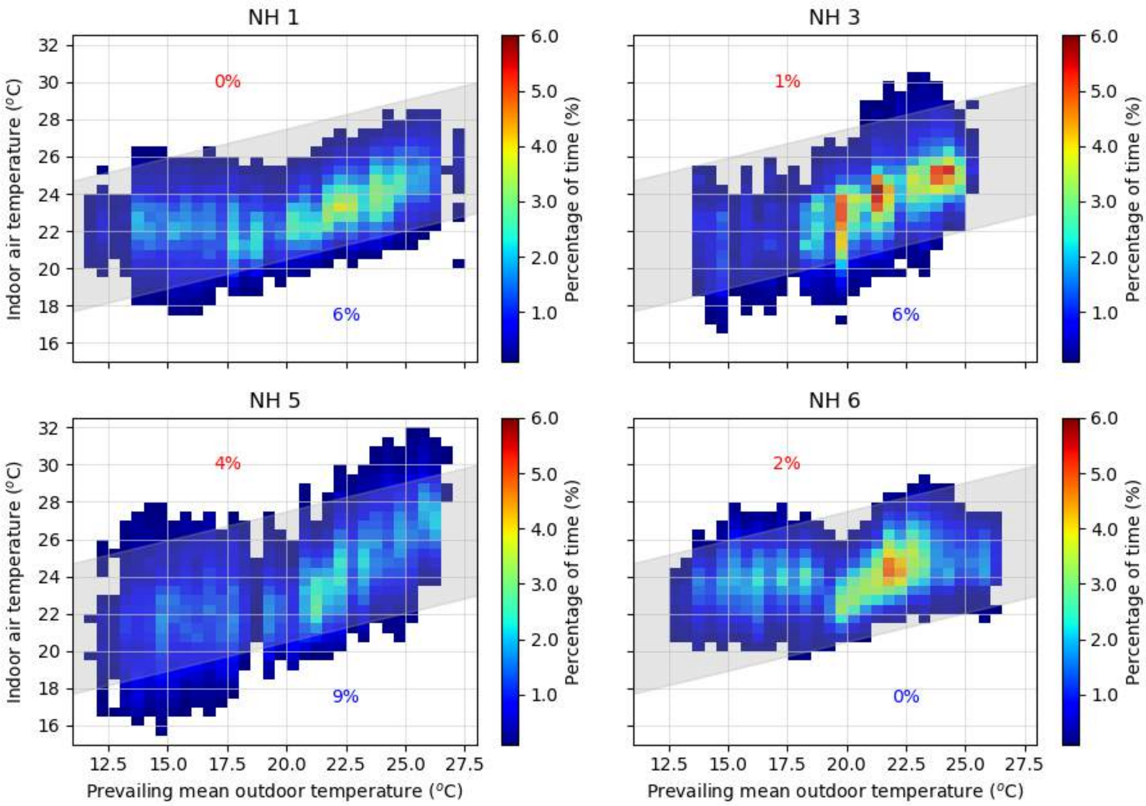


Figure 4. Experimental data collected in spaces that were not mechanically cooled in summer. The figures also show the 80% acceptability limits of the Adaptive Thermal Comfort zone as defined by ASHRAE 55-2013 and the percentage of time temperature above (red) and below (blue) the comfort zone were recorded indoors.

4.2. Long-term Building Evaluation Questionnaire

A total of 85 staff members completed the long-term evaluation survey described in Section 3.2. Participants completed the questionnaire between 29th of September and 27th of October 2016 and they rated the performance of the facility in which they were working over two separate periods: summer (1/12/2015-29/2/2016), and the winter (1/6/2016-31/08/2016).

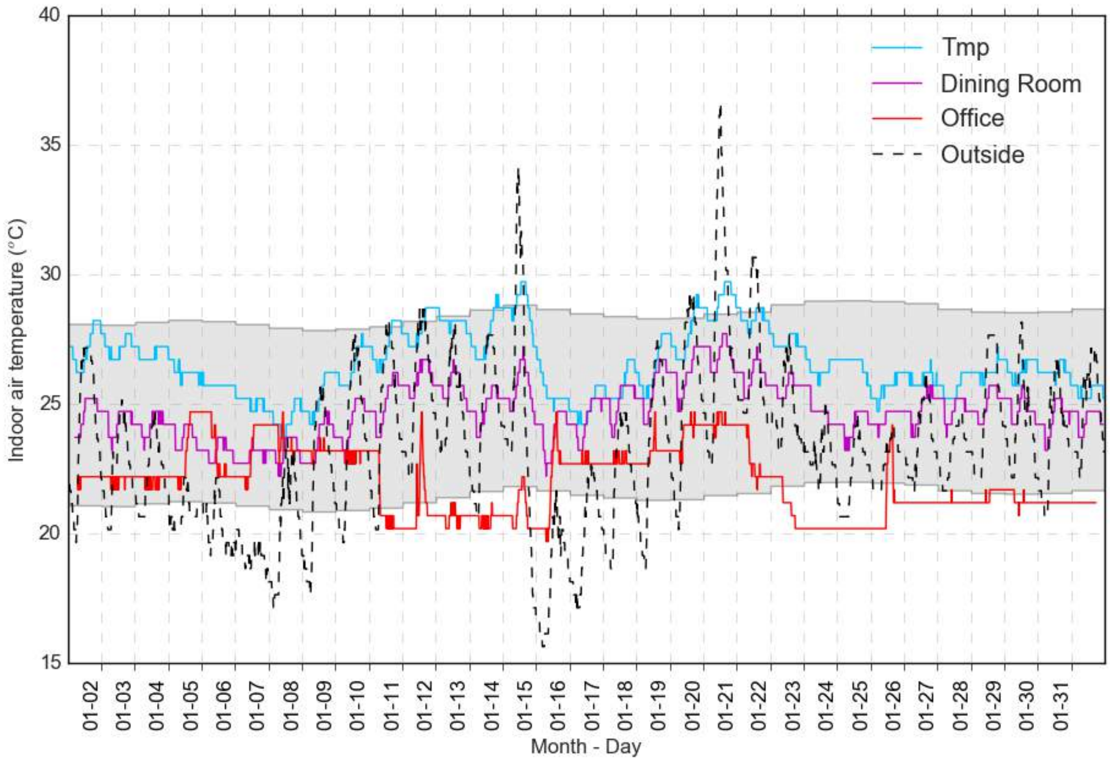


Figure 5. Indoor air temperature data measured in four adjacent spaces of NH 6 between the 10/1/2017 and 2/2/2017. The shaded area shows the comfort zone as defined by the Adaptive Thermal Comfort model.

Table 4 summarizes the characteristics of the staff member sample. The great majority of participants were females (85%), and 52% were aged between 45 and 65 years old. Approximately 42% of the participants were caregivers and 27% were receptionists or administration officers. Participants reported that for approximately 41% of their time they were involved in demanding activities with high metabolic rates (e.g. lifting, walking fast, cooking, etc.), while they spent approximately half of their remaining time doing either activities with low metabolic rates (e.g. a sedentary activity or standing at rest) or medium metabolic rates (e.g. walking slowly or light standing activity). Staff reported that they were spending the majority of their time in rooms with air-conditioning units.

Thermal Comfort

Answers to the question which assessed participants' perceptions of indoor air temperature are presented in Figure 6. Overall newer facilities performed better than older ones; for example, in NH 1 approximately 57% and 56% of the participants rated the temperature to be 'neutral' in summer and winter, respectively. Whereas, more than 40% of the staff working in NH 5 and NH 6 reported the temperature to be either warm or hot in summer and more than 20% of the participants were not satisfied with the indoor environment in winter.

Figure 7 illustrates the fact that staff members who were working at the NH 2 and NH 4 facilities were more satisfied with the indoor air temperature in both seasons, than staff members working in other facilities. This implies that air conditioners effectively reduced the number of hours of uncomfortable indoor temperatures.

Table 4. Characteristics of the study sample.

		NH 1	NH 2	NH 3	NH 4	NH 5	NH 6	Row Total	% Total
N° participants		20	9	9	22	6	19	85	
N° participants/ N° beds		13%	10%	15%	14%	15%	19%		14%
Age	<45	12	5	2	14	2	5	40	47%
	45-65	8	4	6	8	4	14	44	52%
	66-75			1				1	1%
Gender	Female	17	9	8	18	5	15	72	85%
	Male	3		1	4	1	3	12	14%
	Prefer not to say						1	1	1%
Job description	Caregiver	8	1		14	2	9	34	42%
	Administration/Receptionist	6	3	2	4	4	3	22	27%
	Registered nurse	1	2	1	1		3	8	10%
	Recreational activities officer	2		3	1		1	7	9%
	Maintenance officer	2		1	1		2	6	7%
	Physioterapist		1	1				2	2%
	Kitchen staff				1			1	1%
	Laundry staff			1				1	1%
N° hours per week worked	<20	2	2	1	4		4	13	15%
	20-30	9	1	2	3	2	2	19	22%
	30-40	8	5	3	13	2	8	39	46%
	>40	1	1	3	2	2	5	14	16%
Time worked facility	Less than 6 months	1	1		1			3	17%
	6 - 12 months	1	1		6		1	9	4%
	1 - 2 years	4		2	3		2	11	11%
	2 - 5 years	7	3		7	4	5	26	13%
	More than 5 years	7	4	7	5	2	10	35	31%
Percentage working hours	Low metabolic rate	31%	32%	33%	24%	39%	26%		29%
	Medium metabolic rate	22%	34%	47%	27%	21%	35%		30%
	High metabolic rate	46%	34%	19%	49%	40%	39%		41%
Room spend most time	Offices	8	4	2	5	2	1	22	27%
	Residents' bedrooms	4		2	7		3	16	20%
	All	2		1	2		7	12	15%
	Recreation areas	2	1	2	1	1		7	9%
	Bathrooms or showers	2	1		3			6	7%
	Reception		1		1	2	1	5	6%
	Corridors	1	1				3	5	6%
	Sitting Room/Lounge			1	2	1		4	5%
	Dining Room	1					1	2	2%
	Laundry			1				1	1%
	Kitchen				1			1	1%
	Physio room		1					1	1%
Room has heating	No	1					1	2	2%
	Yes	19	9	9	22	6	18	83	98%
Room has cooling	No			2	1		1	4	5%
	Yes	20	9	7	21	6	18	81	95%

4.3. Point-in-time Survey

A total of 509 participants completed the point-in-time questionnaire (322 residents and 187 non-residents); 343 (67% of the total) were females and 157 (31% of the total) were aged 85 years and over. The mean metabolic rate of residents (0.96 met, SD = 0.34) was lower than for non-residents (1.22 met, SD = 0.15) and residents were found to wear significantly more clothing (1.03 clo, SD = 0.60) than their counterpart (0.62 clo, SD = 0.21).

The operative temperature data measured while participants were completing the questionnaire are presented in Figure 8. More than 37% and 60% of residents and non-residents that were exposed to operative temperatures higher than 26°C reported feeling ‘warm’ or ‘hot’, respectively.

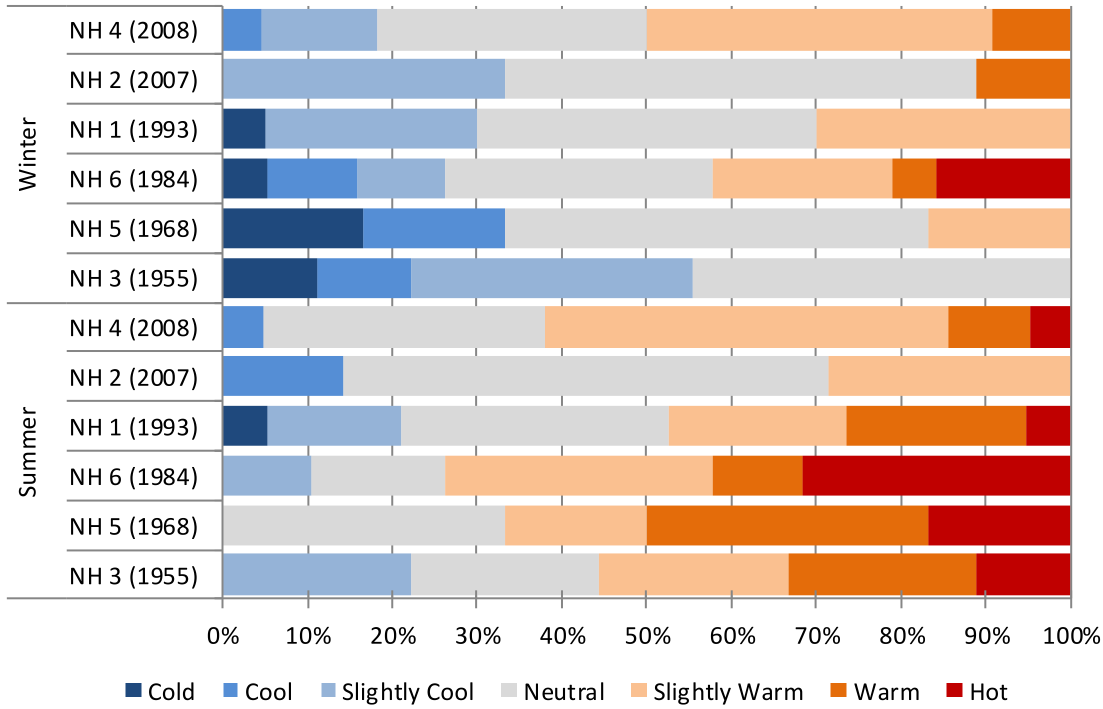


Figure 6. Perception of staff of the indoor thermal environment in summer and winter in the 6 case study facilities. The construction date of each facility is shown in parentheses.

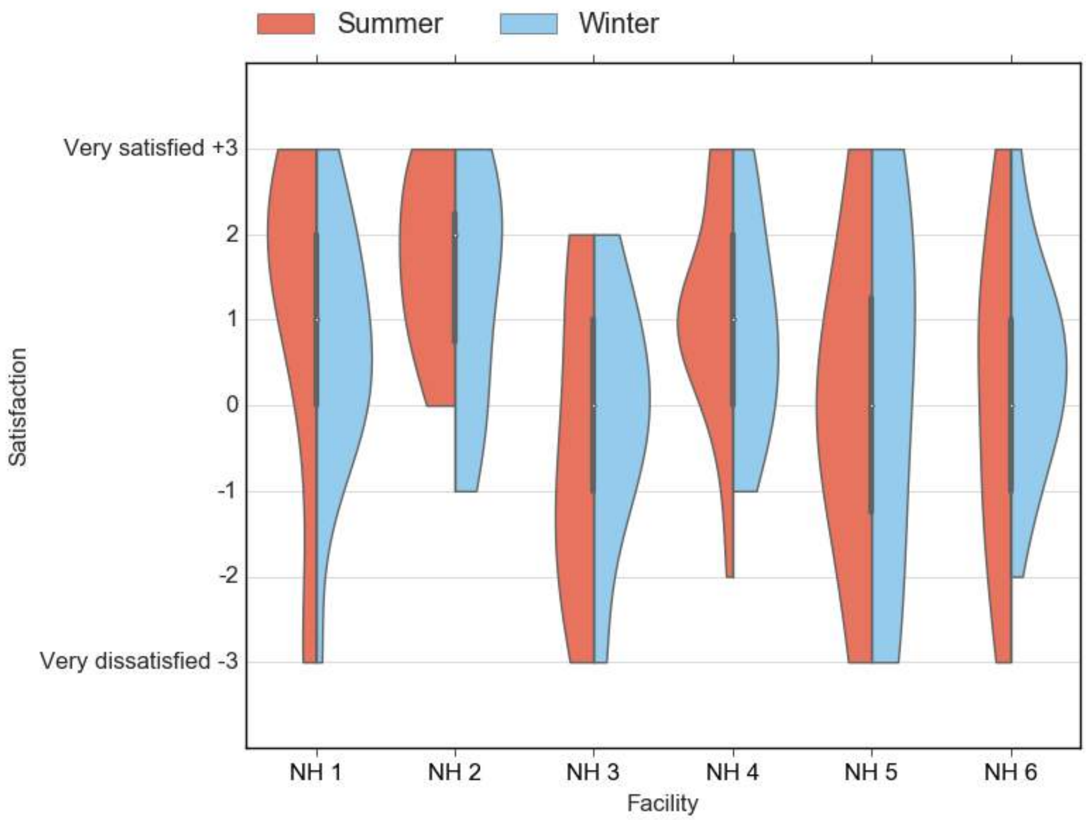


Figure 7. Staff satisfaction with indoor air temperature in summer (red) and winter (blue) as a violin plot.

Among those participants who were wearing light clothes and feeling thermally neutral, the median operative temperature was significantly higher for residents (23.2°C) than for non-residents (22.3°C). In other words, residents felt thermally neutral at higher operative temperatures than non-residents. Insufficient data was available to compare responses between the two cohorts of participants when total clothing insulation exceeded 0.75 clo. Figure 8 also shows that 24 participants (9 non-residents and 15 residents) were exposed to temperatures higher than 28°C, and 3 were exposed to temperatures lower than 18°C.

Adaptive behaviours – Clothing Adjustment

Clothing insulation varied significantly across both groups of participants, ranging from 0.23 clo (summer dress with short sleeves and undergarments) up to 2.87 clo (in bed with blanket and wearing flannel winter clothes) as shown in Figure 9. Active adjustment of clothing was an effective thermal adaptive behaviour that occupants employed to compensate for changes in operative temperature and metabolic rate.

Residents were found to wear more clothes than non-residents. Staff members also actively modified their clothing as a function of the operative temperature; this was possible since they were not obliged to follow a strict dress code.

Adaptive behaviours – Air Velocity Adjustment

Air velocity adjustment was an adaptive behaviour widely adopted by participants to improve their thermal comfort conditions. To facilitate a better understanding of how they modified the environment around them, their thermal sensation votes are plotted against the measured air velocity and operative temperature in Figure 10.

The figure shows that both residents and non-residents increased the air velocity around them as a function of the indoor operative temperature, e.g. by opening windows to maximise natural ventilation, or using ceiling or portable fans. This assisted a fraction of participants to be comfortable even in warm indoor temperatures (26-28°C).

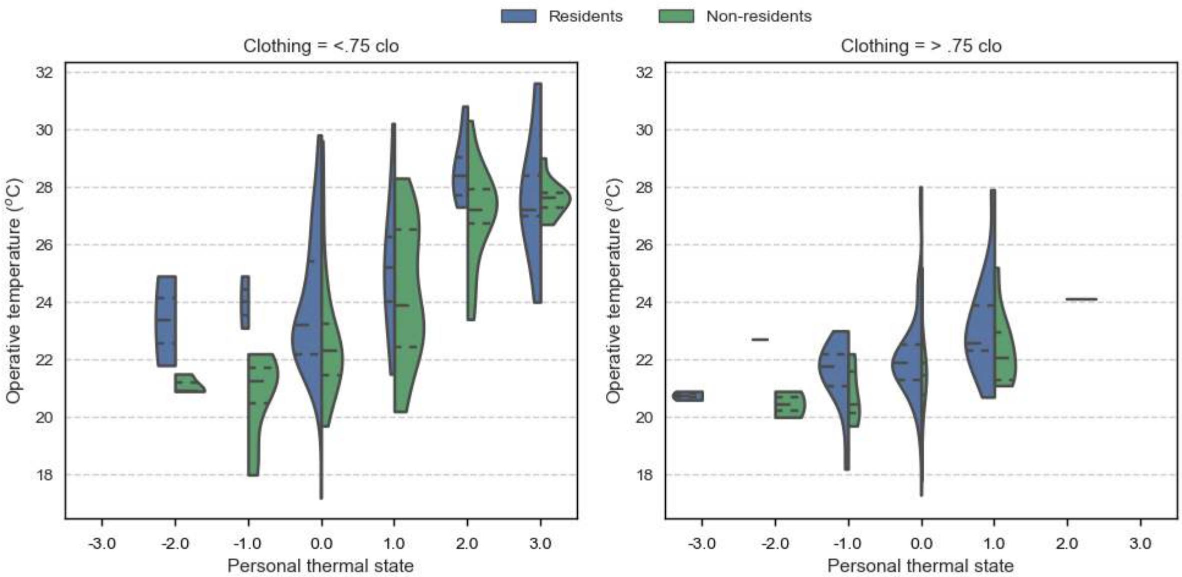


Figure 8. Operative temperature measured during each observation grouped by participant type (residents and non-residents), by personal thermal state vote of participants and total clothing insulation.

Adaptive Thermal Comfort

Thermal sensation votes of 186 participants (130 residents and 56 non-residents) who were not in air-conditioned spaces when they completed the point-in-time questionnaire have been plotted in Figure 11. Approximately 38% of residents and 62% non-residents that were exposed to temperatures higher than 26°C reported feeling thermally uncomfortable (voted 'warm' or 'hot'). Hence, participants in this study preferred significantly lower temperatures than those implied by the upper threshold of the Adaptive Thermal Comfort zone, 80%.

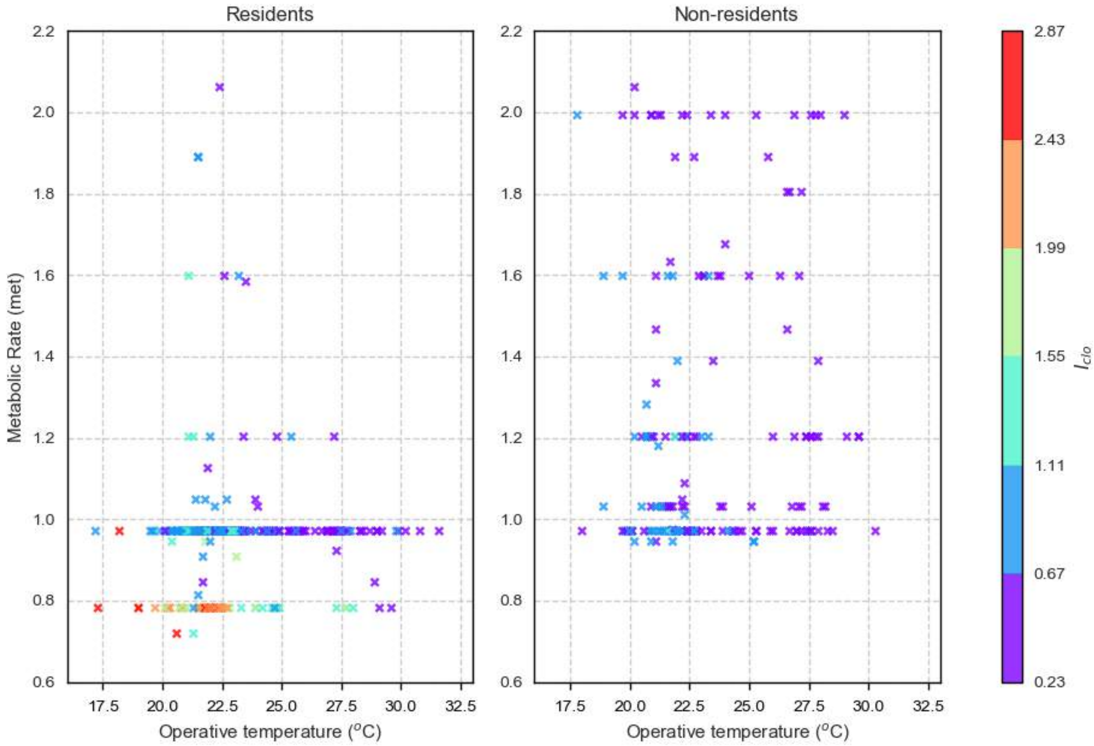


Figure 9. Total clothing insulation plotted in relation to metabolic rate and operative temperature.

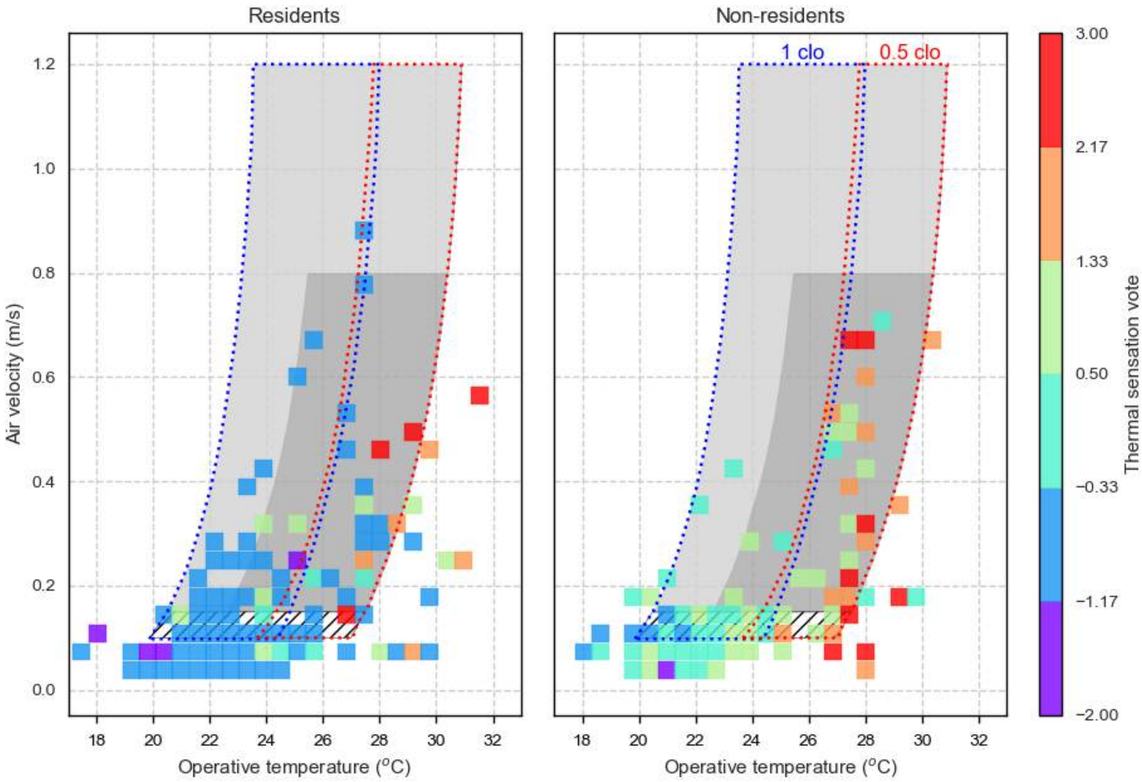


Figure 10. Thermal sensation votes of participants as a function of operative temperature and air velocity. Comfort zones are shown for different clothing insulation as defined by ASHRAE 55-2013. The lightly shaded region indicates acceptable conditions in rooms where occupants do not have control over the local air velocity, the darker region is where occupants do have such control and the hatched region shows the still-air comfort zone.

In addition, results of an ordinal regression data analysis showed that the prevailing mean outdoor temperature was not a statistically significant predictor of the Thermal Sensation Votes of participants ($p > .05$), but the indoor operative temperature was ($p < .05$). In other words, this field study showed that occupant perceptions of their thermal environment was primarily influenced by the indoor thermal conditions with no significant impact from the outdoor environment. This could be explained in part by the fact that often residents of nursing homes spend a very limited portion of their time outdoors.

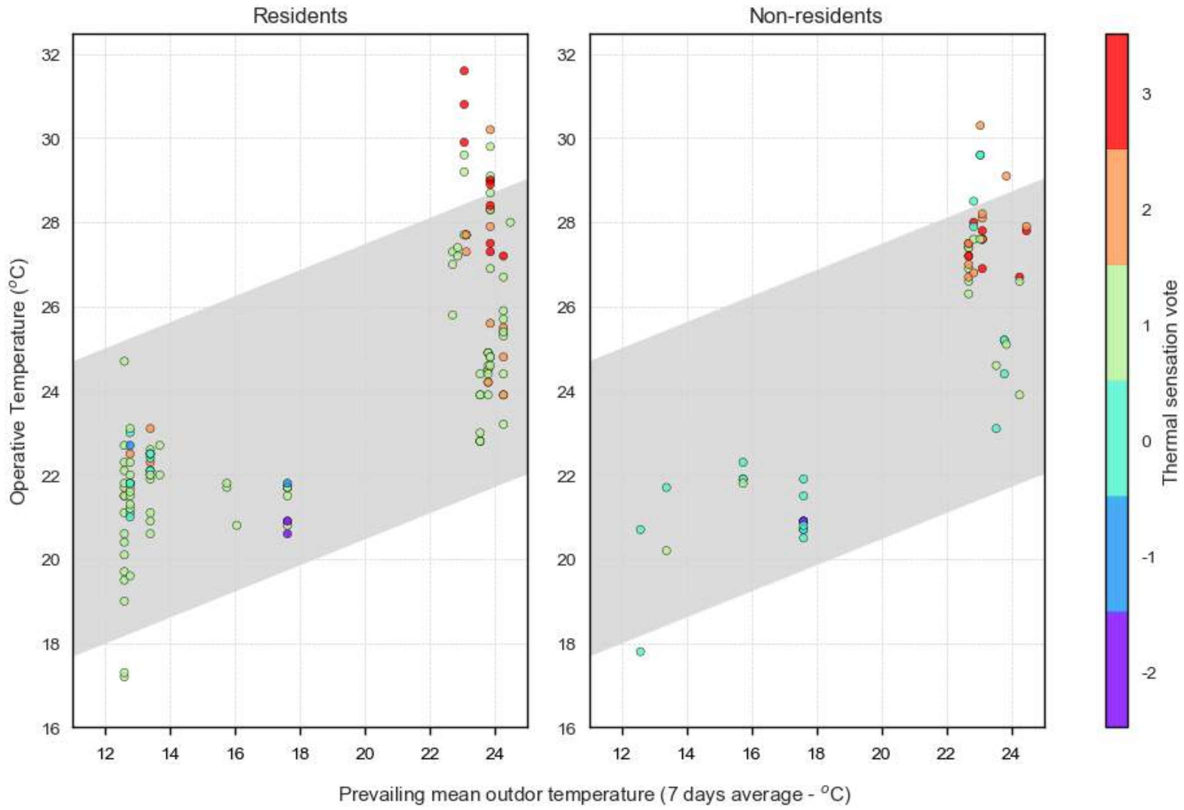


Figure 11. Experimental data displayed on the 80% acceptability limit of the Adaptive Thermal Comfort zone as defined in ASHRAE 55-2013 (ASHRAE, 2013).

5. Discussion

The field data collected showed that occupants of older nursing homes were exposed to significant indoor temperature variations throughout the year. As a result, staff members reported that old facilities were 'hot' in summer and 'cold' in winter. Newer facilities which were fully air conditioned performed better than older ones, however, results showed that air conditioners were not always properly operated. Similar results were obtained by Gupta et al (2017) who investigated magnitude, causes, preparedness and remedies for overheating in nursing homes (Gupta et al, 2017). Gupta found that nursing homes were often overheated in summer, and very few strategies were implemented to mitigated this problem since there was a lack of awareness of the possible impacts that 'hot' temperatures may have on health of residents.

Nursing homes should be designed and operated using strategies that could significantly reduce cooling and heating loads (e.g. insulation, shading, thermal mass, enhance natural ventilation) whilst providing a comfortable environment for both residents and staff members. Furthermore, staff should be trained on how to properly operate air-conditioners and how to provide thermal care to residents. Walker et al (2015) observed that in care homes non-trained staff members, who may not have a clear understanding of how the HVAC system works, are often required to make adjustments of the heating and cooling system. In the present study, inappropriate operation of air-conditioners exacerbated discomfort in older facilities and this appeared to be the primary cause of high temperature gradients between adjacent zones.

A key finding of the point-in-time survey was that residents preferred warmer temperatures (0.9°C) and wore more clothes on average than non-residents. Similar results were previously obtained by Schellen et al. (2010) and Hwang and Chen (2010) who also observed that older adults preferred warmer temperatures than the adult population. In this study, the great majority of participants effectively adjusted their clothing insulation and modified their surrounding environment (e.g. used electric fans, opened windows) to achieve thermal neutrality with their environment.

Finally our results showed that both residents and non-residents preferred to be exposed to cooler temperatures than those indicated by the upper threshold of the Adaptive Thermal Comfort model. Arguably an Adaptive Thermal Comfort zone that increases linearly without limit as a function of the prevailing mean outdoor temperature may not be appropriate for this cohort of people. Similarly, Gupta et al. (2017) suggested that the use of the adaptive thermal comfort model for assessing the risk of overheating in nursing homes may not be appropriate since residents are less able to adapt to their local environment.

6. Conclusion

The primary aim of this research was to assess the quality of the thermal environment of six Australian nursing homes, and to understand and quantify the impacts of the thermal environment on the perceptions and comfort of occupants.

Our findings add quantitative evidence on how some Australian nursing homes are performing in regards to thermal comfort. Some of the case study facilities failed to provide ideal thermal care to residents since insufficient attention was given to ensuring that residents were not exposed to 'hot' and/or 'cold' temperatures. The aged care sector should, therefore, increase its awareness on the importance of providing thermal care, to ensure that residents of nursing homes receive high standard of care.

Further research would be beneficial to support the development of best practice guidelines on how to operate heating/cooling systems in facilities that have a fraction of rooms that are air conditioned, with the remainder being naturally ventilated, which is often the case in older nursing homes.

7. References

AACQA, 2011. *Accreditation & Standards*. Paramatta: Australian Aged Care Quality Agency.

ACFA, 2016. *Fourth report on the Funding and Financing of the Aged Care Sector*. Canberra: Aged Care Financing Authority.

AIHW, 2017a. *About ageing in Australia - Australian Institute of Health and Welfare*. Available at: http://www.aihw.gov.au/ageing/about/ (Accessed: 23 January 2017).

AIHW, 2017b. *Residential aged care facility - Australian Institute of Health and Welfare*. Available at: http://meteor.aihw.gov.au/content/index.phtml/itemId/384424 (Accessed: 17 September 2017).

ASHRAE, 2013. *55-2013 Thermal Environmental Conditions for Human Occupancy*. Atlanta: American National Standards Institute and American Society of Heating Refrigerating and Air-Conditioning Engineers.

CBE, 2014. *Occupant Indoor Environmental Quality (IEQ) Survey and Building Benchmarking*, Center for the Built Environment, University of California Berkeley. Available at: http://www.cbe.berkeley.edu/research/briefs-survey.htm (Accessed: 21 November 2016).

DSS, 2014. 'The Residential Care Manual (Australian Department of Social Services)'. Australian Government - Department of Social Services.

Gupta, R., Barnfield, L., Gregg, M. 2017. Overheating in care settings: magnitude, causes, preparedness and remedies. *Building Research and Information*, *45*(1–2), 83–101.

Hwang, R.-L., Chen, C.-P. 2010. Field study on behaviors and adaptation of elderly people and their thermal comfort requirements in residential environments. *Indoor Air*, *20*(3), 235–45.

ISO, 1998. *7726 Ergonomics of the thermal environment: instruments for measuring physical quantities physiques*. Geneva: International Organization for Standardization.

ISO, 2005. *7730 Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*. Geneva: International Organization for Standardization.

Lin, Z., Deng, S., 2008. A study on the thermal comfort in sleeping environments in the subtropics—Measuring the total insulation values for the bedding systems commonly used in the subtropics, *Building and Environment*, 43(5), pp. 905–916.

van Marken Lichtenbelt, W., Hanssen, M., Pallubinsky, H., Kingma, B., Schellen, L., 2017. Healthy excursions outside the thermal comfort zone, *Building Research and Information*. Taylor & Francis, 3218(September), pp. 1–9.

Marquardt, G., Schmieg, P., 2009. Dementia-friendly architecture: environments that facilitate wayfinding in nursing homes., *American journal of Alzheimer's disease and other dementias*, 24(4), pp. 333–40.

Mendes, A., Bonassi, S., Aguiar, L., Pereira, C., Neves, P., Silva, S., Mendes, D., Guimarães, L., Moroni, R., Teixeira, J., 2015. Indoor air quality and thermal comfort in elderly care centers, *Urban Climate*. Elsevier Ltd, 14(3), pp. 486–501.

OEH 2014) *Aged-care toolkit*. Sydney: Australian Office of Environment and Heritage.

Peretti, C., Schiavon, S., 2011. Indoor environmental quality surveys. A brief literature review, *12th International Conference on Indoor Air Quality and Climate 2011*, pp. 1331–1336.

Schellen, L., van Marken Lichtenbelt, W. D., Loomans, M. G. L. C., Toftum, J., de Wit, M. H. 2010. Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition. *Indoor Air*, *20*(4), 273–283.

Tartarini, F., Cooper, P., Fleming, R., 2017. Indoor Air Temperature and Agitation of Nursing Home Residents with Dementia, *American Journal of Alzheimer's Disease and other Dementias*, 32(5).

Tartarini, F., Cooper, P., Fleming, R., 2017. Thermal environment and thermal sensations of occupants of nursing homes: a field study, *Procedia Engineering - International High-Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016*, 180, pp. 373–382.

UN, 2013. *World Population Ageing, 2013*. New York: United Nations.

WHO, UNEP, 1990. *Indoor environment: health aspects of air quality, thermal environment, light and noise*. Geneva: World Health Organization; United Nations Environmental Programme.

Wong, J., Skitmore, M., Buys, L., Wang, K., 2014. The effects of the indoor environment of residential care homes on dementia suffers in Hong Kong: A critical incident technique approach, *Building and Environment*. Elsevier Ltd, 73, pp. 32–39.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

The influence of outdoor transient conditions on the dynamic response of pedestrian thermal comfort in high-density cities

Kevin Ka-Lun Lau[1,2,3], Yuan Shi[4], Edward Yan-Yung Ng[1,3,4]

[1] Institute of Future Cities, The Chinese University of Hong Kong, Hong Kong, kevinlau@cuhk.edu.hk;
[2] CUHK Jockey Club Institute of Ageing, The Chinese University of Hong Kong, Hong Kong
[3] Institute of Environment, Energy and Sustainability, The Chinese University of Hong Kong, Hong Kong
[4] School of Architecture, The Chinese University of Hong Kong, Hong Kong

Abstract: In high-density cities, the highly variable environmental conditions within short walking distances result in a considerable influence on pedestrians' thermal comfort when they travel within the urban environment. Conventional studies adopted the "static" approach which is insufficient to consider the transient nature, and hence requires a new approach to incorporate the dynamic response of human thermal comfort to inform urban geometry design. This study aims to investigate how people's thermal sensation and pleasure respond to the changing environmental conditions. Subjects were asked to perform two walking routes with thermal sensation vote (TSV) and thermal pleasure vote (TPV) asked at designated points. Meteorological parameters were measured for the calculation of physiological equivalent temperature. Parameters of urban geometry were also acquired from field measurements and geographical information system. Results showed that TSV and TPV showed remarkable differences under partially cloudy and clear sky conditions. Their relationship also showed the possible effect of thermal alliesthesia due to the higher magnitude of response of TPV. Results of the autocorrelation analysis implied the existence of potential thresholds for the level of tolerance to unfavourable thermal conditions. Further work includes the design of walking routes to define such thresholds and the development of practical design recommendations.

Keywords: Outdoor transient conditions, pedestrian thermal comfort, dynamic response, urban geometry, high-density cities

1. Introduction

Urban structures resulted in complex and highly variable environmental conditions within short walking distances in high-density cities. It influences the level of thermal comfort when pedestrians travel within such complex urban settings. The conventional static approach is not sufficient to take into account the transient conditions in outdoor environment. The dynamic response of pedestrian's thermal comfort is therefore important to the design of urban geometry.

Previous studies did not fully address the relationship between the history of environmental exposure and the dynamic response of pedestrian's thermal comfort because the majority of them focused on the instantaneous response of thermal sensation or comfort to the surrounding environment (Nikolopoulou and Lykoudis, 2006). Potvin (2000) suggested that thermal transients result in different responses of thermal regulation of human body. As such, the rate of transition is important to maintain or improve thermal comfort under changing environmental conditions.

Thermal walks were previously performed in European cities to study the variations in pedestrian thermal comfort in outdoor environment (Vasilikou and Nikolopoulou, 2013). It was shown that pedestrians were able to perceive the variations in environmental conditions during the walks. One recent study studied the dynamic response of pedestrian thermal comfort using a mobile measurement system to obtain subjects' thermal sensation along a designated route (Nakayoshi et al., 2015). De Dear (2011) suggested that it was influenced by the cutaneous thermoreceptors responding to subtle environmental changes, which confirms the importance of pedestrians' physiological response and thermal history.

This study aims to examine the relationship between dynamic response of pedestrian thermal comfort and variations in micrometeorological conditions along a designated walking route in a high-density urban area in Hong Kong. Findings of this study will provide insights for understanding the dynamic response of thermal comfort when pedestrians travel within urban environment and the level of tolerance to thermal discomfort during their walking trips. It contributes to the improvement of outdoor spaces and walking environment in high-density cities.

2. Methodology

2.1. Experimental Design

Longitudinal survey was conducted in a high-density commercial area in Hong Kong. The study area is characterized by high-rise buildings and compact settings, as well as high-level of pedestrian activities. Sky view factor (SVF) was calculated to represent the compactness of the urban geometry in the study area. The walking route was designed to cover the variations in urban geometry and the survey was conducted at designated survey points (Figure 1). Subjects were asked to report their thermal sensation vote (TSV) on the ASHRAE seven-point scale using a mobile application (Figure 2) at each survey point which are approximately three minutes apart. Thermal pleasure vote (TPV) was also asked to obtain the level of pleasure/comfort the subject experienced. Skin temperature was also recorded to examine the physiological effect on thermal sensation and pleasure. The background meteorological conditions of the days when the surveys were conducted are shown in Table 1. The surveys were conducted between 14h and 16h under three types of sky conditions, namely clear, partially cloudy and overcast, to represent the typically hot summer conditions in Hong Kong.

Figure 1. Walking route of the present study (left) and fisheye photos of survey points (right).

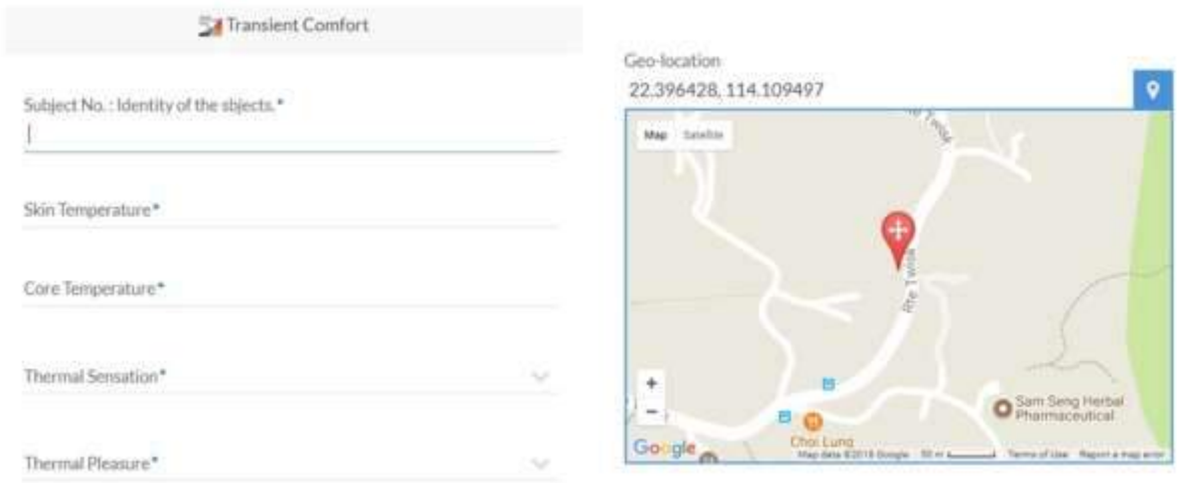


Figure 2. Mobile application to record the response from subjects.

Table 1. Background meteorological conditions during the survey.

Date	T_a (°C)	RH (%)	Wind Dir	v (m/s)	Sky Condition	Cloud (%)	Sunshine Hour
20170510	28.3-28.9	69-75	Southeast	1.9-3.1	Partially cloudy	84	1.3
20170529	28.9-29.9	58-64	Southeast	2.4-6.4	Clear sky	38	10.5

2.2. Meteorological Measurements

Mobile meteorological stations were used to record the simultaneous meteorological conditions during the survey (Figure 3). It is composed of a TESTO480 Digital Microclimatic Sensor Set for measuring air temperature (T_a), relative humidity (RH) and wind speed (v), and a custom-made globe thermometer composed of a thermocouple wire (TESTO flexible Teflon type K) held in the middle of a 38-mm black table tennis ball, which is designed for decreasing the response time during mobile measurements and capturing the variable conditions in outdoor environment (Humphreys, 1977; Nikolopoulou et al., 1999). Mean radiant temperature (T_{mrt}) was then calculated from globe temperature (T_g) based on the following equation (Thorsson et al., 2007).

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.10 * 10^8 * v^{0.6}}{\varepsilon * D^{0.4}} \left(T_g - T_a\right) \right]^{1/4} - 273.15$$

where ε is emissivity (0.95 for a black globe) and D is globe diameter. Clothing of each subject was recorded, and the level of metabolic activity is assumed to be 2.0 met, representing a slow walking speed of 3.0 km/h for pedestrian activities in commercial/shopping area (Fanger, 1973). Based on the above meteorological and human parameters, physiological equivalent temperature (PET) was calculated and used as an objective indicator of pedestrian thermal comfort.

2.3. Statistical Analysis

Thermal sensation vote (TSV), thermal pleasure vote (TPV) and skin temperature (T_{skin}) were selected as dependent variables. Meteorological variables such as Ta, RH, v and Tmrt were independent variables to investigate the effect of meteorological conditions on pedestrian thermal comfort. In addition, T_{skin} and PET were also used as predictor to determine the physiological pathway of thermal comfort. Two types of statistical analyses were conducted in this study, namely Spearman correlation analysis and cross-correlation analysis. Spearman correlation analysis was conducted to examine the association between thermal sensation, thermal pleasure, skin temperature and instantaneous level of meteorological variables. On the other hand, cross-correlations between the above variables were analysed to determine the time lag(s) of meteorological variables preceding the thermal sensation reported by subjects that the data series showed the highest correlation.

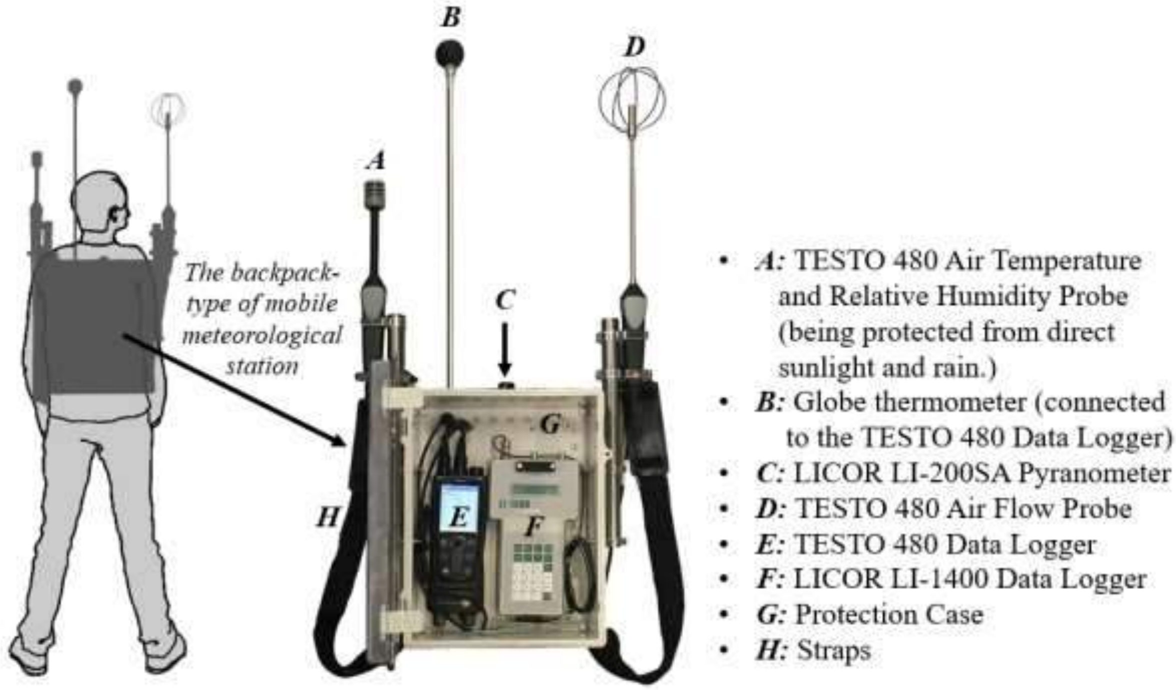


Figure 3. Instrumental settings of the mobile meteorological station.

3. Results and Discussion

3.1. Temporal Variation of Thermal Comfort and Meteorological Variables

Meteorological conditions of the two survey days (partially cloudy and clear days) along the walking route are shown in Figure 4. Meteorological conditions recorded on cloudy day did not fluctuate as much as those recorded on the clear day. On the clear day, T_a reached up to 31.5°C at several exposed points while T_a is up to 2.5°C lower at sheltered locations (Point 21). Wind speed was also more variable on the clear day, with a maximum wind speed near 4m/s recorded along the main road. T_{mrt} and PET were also variable due to the complex street geometry. Meanwhile, the highest PET values recorded on partially cloudy and sunny days were 31.2°C and 32.2 respectively.

Figure 5 shows the temporal variation of TSV, TPV and T_{skin} on partially and clear days. The effect of shading is more prominent on thermal sensation on the sunny day as TSV was about 1 point lower in the sheltered locations. However, such a difference was not observed on the partially cloudy day. In the first quarter of the walking route (Point 1-8), TSV was generally higher than the second quarter (9-16) since there was a sudden drop in TSV. Such a decrease coincides with the drop in T_a and the increase in wind speed. In the latter half of the walking route, TSV was generally higher due to the more exposed urban geometry. T_a was also higher in this more exposed section of the walking route. Similar to the first half of the walking route, higher wind speed led to lower TSV, reiterating the importance of urban air ventilation in improving pedestrian-level thermal comfort. In addition, TPV exhibited as a reciprocal of TSV, corresponding consistently to TSV under partially cloudy conditions. However, under clear sky conditions, the response of TPV was slightly higher, i.e. subjects felt more pleased with the decrease in TSV. Such a response echoes with the concept of "thermal alliesthesia" (Parkinson and de dear, 2015). It also implies the importance of a diverse thermal environment which enables people to maintain thermally comfortable conditions in the walking environment.

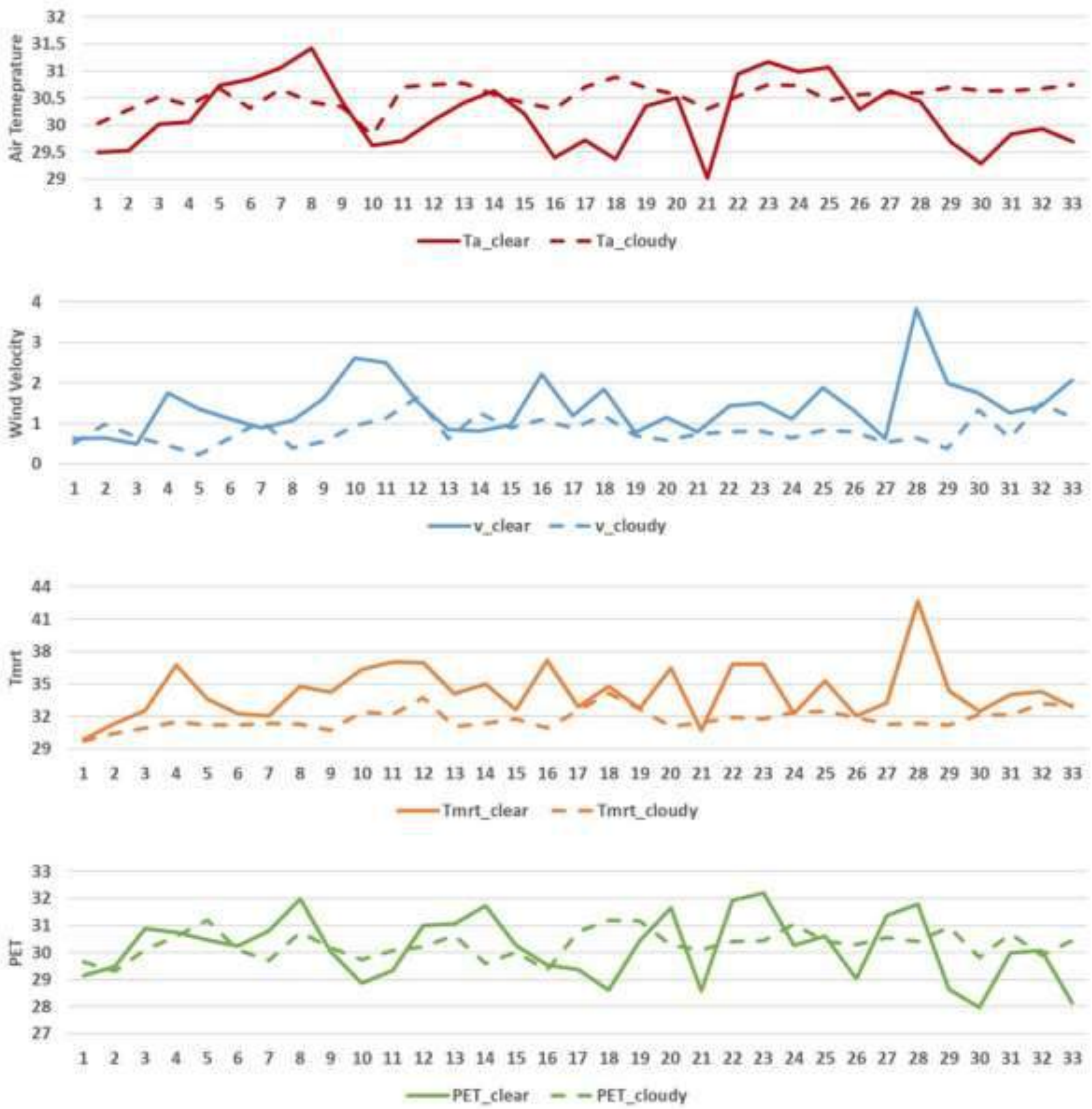


Figure 4. Meteorological conditions along the walking route on the two survey days.

3.2. Correlations between Thermal Comfort and Meteorological Variables

Table 2 shows the correlations between TSV, TPV, T_{skin} and meteorological variables under both partially cloudy and clear sky conditions. TSV and TPV are highly correlated with each other with slightly lower correlation observed for clear sky conditions. It further proved the higher magnitude of response of TPV due to the possible effect of thermal alliesthesia. T_{skin} was found to be significantly correlated with both TSV and TPV under clear sky conditions, which suggests that human skins are sensitive to the changes in environmental conditions and hence influence human perception of thermal comfort. In addition, T_{skin} was significantly correlated with T_a and PET for clear sky conditions. Although sensible heat exchange with air is rather minimal in outdoor environment, the longwave radiation from surrounding heated surface and hot air plays an important role in skin temperature and influences the physiological response of human body (Arens and Zhang, 2006).

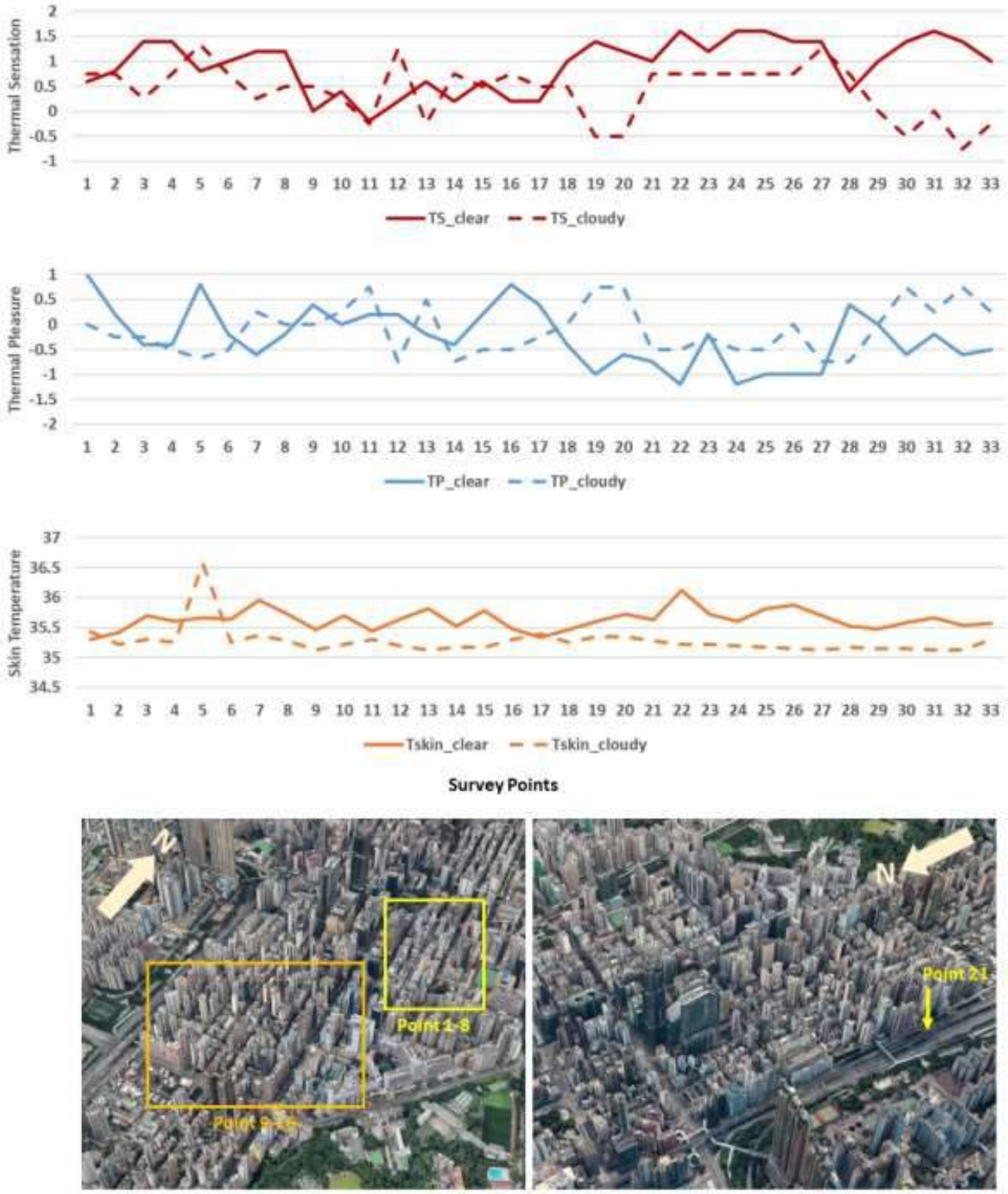


Figure 5. Meteorological conditions along the walking route on the clear day (29 May 2017).

Among the meteorological variables, wind speed was found to be significantly correlated with T_{mrt} under both partially cloudy and clear sky conditions. It was because higher wind speed was experienced along the more sun-exposed main road in the latter half of the walking route. T_{mrt} is significantly correlated with PET only under clear sky conditions due to the predominant influence of solar radiation on PET. Under partially cloudy conditions, the relatively stable PET throughout the walking routes did not have any significant relationship with both thermal sensation and T_{mrt}.

3.3. Autocorrelation Analysis

Autocorrelation analysis was conducted to examine internal associations between TSV and TPV throughout the walking route. Figure 6 shows the autocorrelation functions of TSV and TPV under both partially cloudy and clear sky conditions. It was found that under partially cloudy conditions, there were no significant autocorrelations present except for the lag-5 of the TPV series (-0.433), with similar pattern observed in both TSV and TPV series despite of statistical insignificance. It suggests that there may be an inverse relationship between the instantaneous response and the thermal pleasure the subjects felt 10-15 minutes ago (approximate time for five survey points), implying that there is a possible threshold of short-term acclimatization.

Table 2. Spearman correlations between thermal comfort and meteorological variables. Bolded values indicate the correlations are as statistically significant at the 0.05 level.

Partially cloudy day

	TSV	*TPV*	T_{skin}	*V*	T_a	T_{mrt}
TSV						
TPV	**-0.889**					
T_{skin}	0.031	0.058				
v	-0.197	0.146	-0.049			
T_a	-0.261	0.215	-0.079	0.228		
T_{mrt}	-0.206	0.147	-0.106	**0.579**	**0.522**	
PET	0.004	-0.028	0.006	**-0.461**	**0.571**	0.297

Clear day

	TSV	*TPV*	T_{skin}	*V*	T_a	T_{mrt}
TSV						
TPV	**-0.789**					
T_{skin}	**0.502**	**-0.493**				
v	-0.203	0.213	-0.189			
T_a	0.299	-0.279	**0.596**	-0.188		
T_{mrt}	-0.224	0.193	0.006	**0.661**	0.157	
PET	0.152	-0.112	**0.502**	-0.261	**0.797**	**0.403**

For clear sky conditions, significant autocorrelations were observed for the lag-1 of both TSV and TPV series (0.600 and 0.394), indicating that subjects' thermal sensation and pleasure are dependent on their immediate thermal history. The positive correlation between the TSV and its lag-1 series suggests that subjects' thermal sensation tends to be maintained in short time period. Thermal sensation due to sun exposure was likely to persist even when there was a change in micrometeorological conditions. On the other hand, it also implies a possible threshold for tolerating the unfavourable conditions if thermal sensation persists even when pedestrians travel under such unfavourable conditions.

4. Conclusions

A longitudinal survey of thermal comfort was conducted in summer afternoon in sub-tropical high-density cities where urban geometry is highly variable within short distances. TSV and TPV showed remarkable differences under partially cloudy and clear sky conditions. The relationship between TSV and TPV also showed the possible effect of thermal alliesthesia due to the higher magnitude of response of TPV. Results of the autocorrelation analysis implied the existence of potential thresholds for the level of tolerance to unfavourable thermal conditions. Further work includes the design of walking routes to define such thresholds and the development of practical design recommendations.

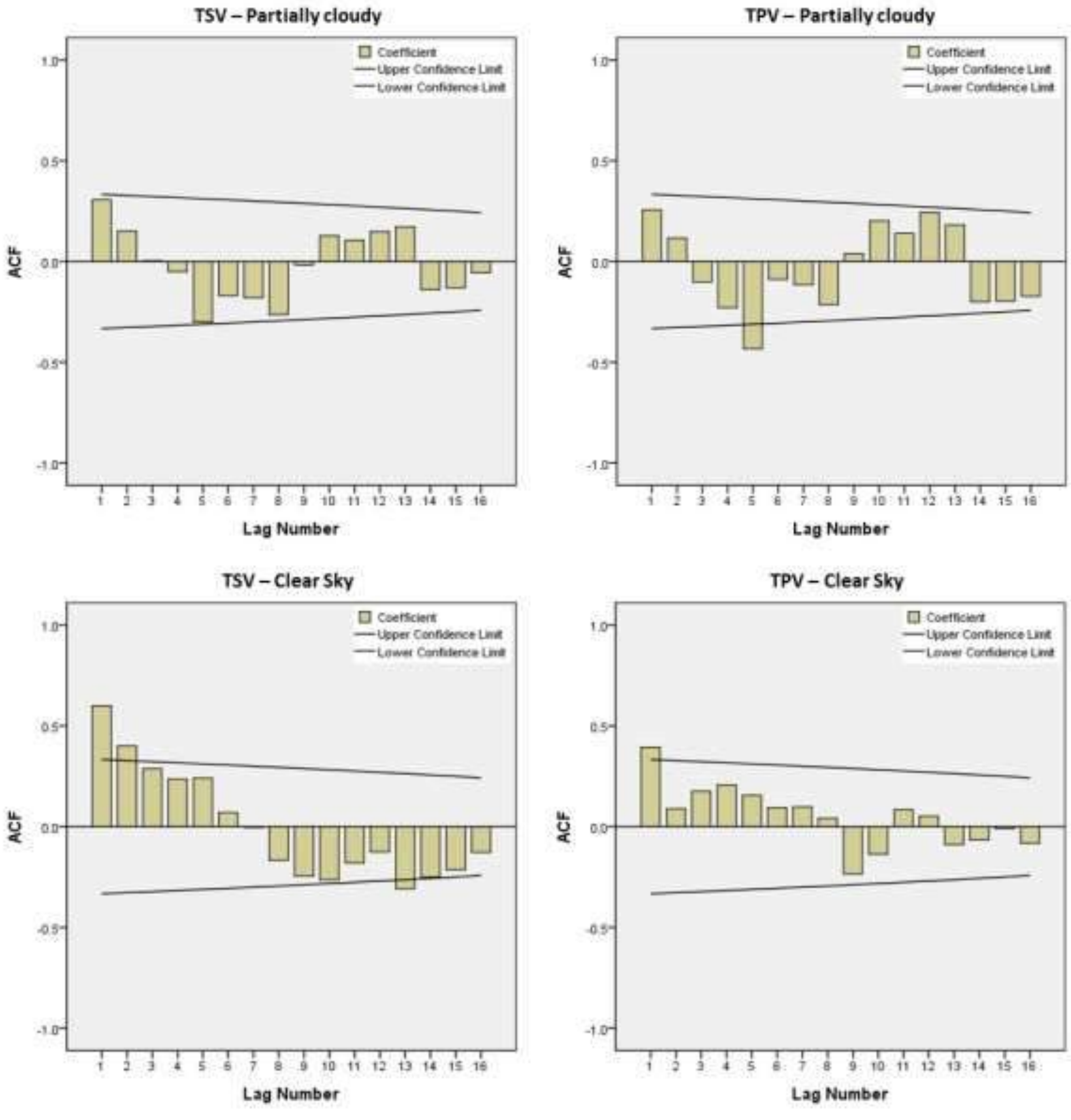


Figure 6. Meteorological conditions along the walking route on the clear day (29 May 2017).

5. References

Arens, E., Zhang, H., 2006. The skin's role in human thermoregulation and comfort. In: Thermal and Moisture Transport in Fibrous Materials, N Pan P Gibson (eds). Woodhead Publishing Limited, England.

de Dear, R., 2011. Revisiting an old hypothesis of human thermal perception: Alliesthesia. *Building Research and Information*, 39(2), pp 108-117.

Humphreys, M.A., 1977. The optimum diameter for a globe thermometer for use indoors. *Building Research Establishment Current Paper*, 78(9), 1-5.

Nakayoshi, M., Kanda, M., Shi, R., de Dear, R., 2015. Outdoor thermal physiology along human pathways: a study using a wearable measurement system. *International Journal of Biometeorology*, 59, 503-515.

Nikolopoulou, M., Lykoudis, S., 2006. Thermal Comfort in Outdoor Urban Spaces: analysis across different European countries. *Building and Environment*, 41(11). pp 1455-1470.

Nikolopoulou, M., Baker, N., Steemers, K., 1999. Improvements to the globe thermometer for outdoor use. *Architectural Science Review*, 42, 27-34.

Parkinson, T., and de Dear, R., 2015. Thermal pleasure in built environments: physiology of alliesthesia, *Building Research & Information* 43(3), 288–301.

Potvin, A., 2000. Assessing the microclimate of urban transitional spaces. *Proceedings of PLEA2000* (Passive Low Energy Architecture), Cambridge, UK, July 2000.

Thorsson, S., Lindberg, F., Eliasson, I., Holmer, B., 2007. Different methods for estimating the mean radiant temperature in an outdoor urban setting, *International Journal of Climatology*, 27, 1983-1993.

Vasilikou, C., Nikolopoulou, M., 2013. Thermal walks: Identifying pedestrian thermal comfort variations in the urban continuum of historic city centres. *PLEA2013 - 29th Conference*, Sustainable Architecture for a Renewable Future, Munich, Germany 10-12 September 2013.

Acknowledgement

This study is supported by General Research Fund, Research Grant Council, Hong Kong (Grant no.: 14629516) and Vice-Chancellor Discretionary Fund, The Chinese University of Hong Kong.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

From indoors to outdoors and in-transition; thermal comfort across different operation contexts

Marialena Nikolopoulou[1], Alkis Kotopouleas[1] and Spyridon Lykoudis[2]

[1] Centre for Architecture and Sustainable Environment (CASE), Kent School of Architecture, University of Kent, Canterbury CT2 7NZ, M.Nikolopoulou@kent.ac.uk, A.G.Kotopouleas@kent.ac.uk
[2] Independent Researcher, Athens, Greece, slykoud@yahoo.com

Abstract: This paper focuses on the investigation of thermal comfort conditions in three very different operational contexts using meta-analysis of different studies within a similar climatic context in the UK. This includes extensive surveys indoors from offices, outdoors from urban areas, as well as indoors from airport terminals. Recent research in airport terminal buildings has highlighted that there are very different user groups, with diverse requirements for thermal comfort in such facilities. The paper investigates the hypothesis that staff working in the different areas have needs more similar to those of staff working in offices, while passengers use the building as a transition area with very different requirements and hence closer to the outdoor environment. Analysing and comparing the thermal comfort conditions from the different contexts, it explores the role of adaptation for thermal comfort attainment and satisfaction with the environment and the similarities of very different operational contexts in terms of their thermal comfort characteristics. Finally, the paper highlighted techniques for the potential transformation of thermal comfort scales, which can enable comparison between different types of surveys and inform the wider thermal comfort debate.

Keywords: meta-analysis, adaptation, scale transformation, surveys

1. Introduction

In the last 20 years, the field of thermal comfort has witnessed a significant increase in thermal comfort surveys in different operational contexts, which has provided a broader perspective from which to view comfort in urban environments. It has also enabled us to understand adaptation processes more closely and evaluate the subtle ways which they present themselves and their importance in achieving thermal comfort in different contexts.

This paper focuses on thermal comfort in three very different contexts; in offices, outdoor urban spaces and airport terminals, using meta-analysis of different studies within a similar climatic context in the UK. Recent research in airport terminal buildings has highlighted that there are very different user groups, with diverse requirements for thermal comfort in such facilities (Kotopouleas and Nikolopoulou, 2016). The paper investigates the hypothesis that staff working in the different areas have needs more similar to those of staff working in offices, while passengers use the building as a transition area with very different requirements and hence closer to the outdoor environment. Analysing and comparing the thermal comfort conditions from the different contexts, the paper explores the role of adaptation for thermal comfort attainment and satisfaction with the environment and the similarities of very different operational contexts in terms of their thermal comfort characteristics.

2. Research Framework

Before proceeding with explaining the data sources and methodology employed for the study, it is worth discussing the development of the hypothesis and the reason for the comparison of the different operational contexts. Recent research funded by the EPSRC to minimise the carbon footprint of airport terminal buildings, identified the occurrence of two distinct user groups with consistent differences in thermal comfort requirements (Nikolopoulou and Kotopouleas, 2016). Despite the identical environmental operation context, the analysis highlighted the difference in the way the terminal is perceived as transition vs. indoor workspace for passengers and staff respectively.

Such differences, which could only be justified by personal and cognitive factors discussed in the framework of psychological adaptation (Nikolopoulou and Steemers, 2003), led one of the authors to put forward the hypothesis that adaptive opportunity should in fact be treated as a continuum (Nikolopoulou, 1998, 2004). Nikolopoulou argued that on one end of the spectrum, conditions were fully controlled with no adaptation possible, e.g. in climate chambers, while on the other end, conditions were totally uncontrolled and variable, e.g. outdoors with adaptation developing fully both physically and psychologically (Fig. 1). She speculated that buildings occupied various points in between, according to the degree of adaptation they allowed for. Fully controlled HVAC buildings not allowing interaction between the occupants and the system would be closer to the climate chamber, whereas free-running buildings closer to the outdoor situation.

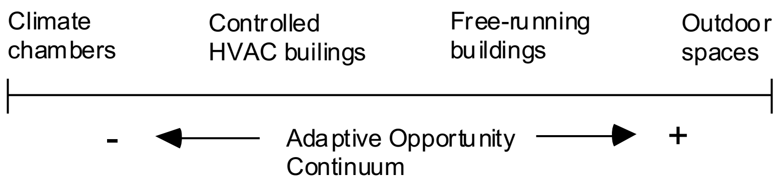


Figure 1: Schematic diagram of the adaptive opportunity continuum (Nikolopoulou, 1998)

Following this continuum, application of theoretical comfort models could then be compared with occupants' thermal comfort conditions. For example, as comfort models have been developed from surveys in climate chambers (e.g. Fanger 1970), it would be expected the two to be identical at the respective end of the spectrum. Moving towards the other end, the biggest difference would be expected for outdoor spaces, where research has indeed highlighted large discrepancies between theoretical models and actual outdoor thermal comfort conditions (Nikolopoulou *et al.*, 2001; Nikolopoulou and Lykoudis, 2006). With the built environment falling in between these two extremes, where the building envelope is sealed and the indoor conditions are fully controlled by a central HVAC system, it would be expected that theoretical models are very close to actual thermal comfort conditions, as a result of minimal adaptive opportunity. Indeed, this was corroborated by de Dear *et al.* (1997), who demonstrated that the PMV model (ISO 7730) describes well the thermal sensations for closely controlled buildings. However, in free-running buildings the difference between the two increases significantly (de Dear *et al.*, 1997). This behaviour could be argued to be due to the higher degree of adaptation where occupants interact with the buildings for environmental control.

Although the above model is simplified, it is reasonable to assume that differences in the degree of adaptation still exist even within each of these generic groups, although of smaller magnitude. For example, in free-running buildings, the degree of adaptive opportunity can vary between a cellular and an open plan room. Similarly, in outdoor areas, there is a variety of spaces, allowing access to sun and shade, etc.

With the recent field surveys from a different building typology, namely airport terminals, where distinct thermal comfort conditions were revealed for different user groups even within the same environment, the speculative model of the adaptive continuum is revisited to evaluate the possible role of adaptive opportunity and identify similarities with other physical contexts.

3. Data sources

The study comprises a review and meta-analysis of three extensive thermal comfort datasets, from different operational contexts including offices, airport terminals and outdoor urban settings. These include the ASHRAE RP-884 database that was used for the development of the first adaptive thermal comfort standard for indoors (ANSI/ASHRAE, 2004), the EU-funded RUROS database for outdoors (Nikolopoulou and Lykoudis, 2006) and the data from the EPSRC-funded project on airport terminals (Kotopouleas and Nikolopoulou, 2016, 2018). The ASHRAE RP-884 and RUROS databases include results from comfort surveys from different countries around the world. To enable comparison, between indoors/outdoors as well as airports, a common geographical ground needed to selected. Hence the focus was on the UK.

Offices were selected for the indoor environment, to enable a better comparison with working conditions of airport staff. The studies selected were by Nicol *et al.* in Oxford (1996) and by Williams in Liverpool, St Helens and Chester (1995). For the outdoor environment, the RUROS studies for the UK included the surveys by Steemers *et al.* in Cambridge (2001-02) and Kang *et al.* in Sheffield (2001-02). Finally, for the airport terminals, the surveys by Nikolopoulou and Kotopouleas from Manchester Terminals 1 and 2 and London City Airport (2013-14) were employed. The studies included summer and winter surveys except from Nicol et al. in Oxford (1996) which was carried out in summer only. In some ways, the comparison was limited to datasets available for the specific criteria in the climatic context investigated, and these were the only ones available to the authors, i.e. through the publicly available datasets for indoors and outdoors and the more recent work on airport terminals. A comparison of the relevant studies for the analysis is shown on Table 1.

Overall, there are 1374 participants in the offices, 3087 in the airports and 1957 in the outdoor surveys. The environmental parameters monitored are similar, including air temperature, globe temperature (Tglobe was not collected for the Williams study; also a black globe was used for indoors and grey globe outdoors for RUROS), relative humidity and air movement. Based on these measurements it was then possible to calculate mean radiant and operative temperatures.

It should be highlighted that the conditions included a mixture of mixed mode (some buildings in winter in Williams' study) and free-running case studies (Nicol's study was in naturally-ventilated buildings, as was some of Williams' buildings, while RUROS by definition was in the naturally occurring outdoor thermal environment). On the other hand, the airports were in full HVAC mode across both seasons.

Subjective data from the participants included thermal sensation, and in most cases information on gender, clothing and metabolic rate was also available. Thermal preference data were not available for the RUROS study; hence this parameter was not included in the analysis. A major difference between the studies indoors and outdoors was that the RUROS project employed a 5-point thermal sensation scale, as opposed to the ASHRAE 7-point scale, which had been introduced to aid the interviewing process of individuals after a pilot study outdoors, in what sometimes could be regarded as unfavourable conditions (Nikolopoulou *et al.,* 2001).

This was an important obstacle for potential comparison; hence it was critical to transpose the 5-point RUROS thermal sensation scale into a 7-point scale which could be directly comparable with the rest of the studies.

Table 1: Summary data of the comfort surveys employed for indoors, outdoors and airport terminals

		Nicol Summer NV[i]	**Williams Summer NV**	**Williams Winter NV**	**Williams Winter Mixed**	**Airports HVAC Summer & Winter**	**RUROS Summer & Winter**
General	Location	Oxford	Liverpool, St Helens and Chester			London & Manchester	Cambridge & Sheffield
	Environment	Indoors	Indoors			Indoors	Outdoors
	Case studies	3 office buildings	8 office buildings			3 airport terminals	4 urban locations
Participants	Sample	877	167	209	121	3087	1957
	Gender	✔	x	x	x	✔	✔
	Clothing ins.	✔	✔	✔	✔	✔	✔
	Thermal sensation	✔	Missing 19	✔	✔	✔	✔(5-point)
	Thermal Pref.	✔	x	x	x	✔	x
Indoor conditions	Tair	✔(at 0.6m)	✔(at 0.6m)	✔(at0.6m)	✔(at 0.6m)	✔(at 1.7m)	n/a
	Tg	✔(at 0.6m)	x	x	x	✔ (at 1.7m)	n/a
	Tmr	Missing 2	✔	✔	✔	✔ (at 1.7m)	n/a
	Top	Missing 2	✔	✔	✔	✔ (at 1.7m)	n/a
	RH%	✔	✔	✔	✔	✔ (at 1.7m)	n/a
	Air movement	missing 215 (at 0.6m)	✔※ (at 0.6m)	✔※ (at 0.6m)	✔※ (at 0.6m)	✔ (at 1.7m)	n/a
Outdoor conditions	Tair	✔[ii]	✔[ii]	✔[ii]	✔[ii]	✔(meteo)	✔
	Tg[iii]	x	x	x	x	x	✔
	Tmr	x	x	x	x	x	✔
	RH%	✔[ii]	✔[ii]	✔[ii]	✔[ii]	✔(meteo)	✔
	Wind speed	x	x	x	x	x	✔

i Naturally Ventilated

ii Available data for min (at 6am) and max (at 3pm)

iii Tglobe was measured with a grey globe outdoors (as opposed to a black globe used indoors)

3.1. Transformation of RUROS 5-point to ASHRAE 7-point thermal sensation scale

Scale transformation has been investigated in other disciplines, particularly psychology, where the use of Likert scales, i.e. scales allowing individuals to express their dis/agreement in a particular statement, is commonly found. Previous studies that looked at 5- and 7-pt scale transformation have proposed two inverse equations for the estimation of equivalences between the two scale formats (Colman and Norris, 1997), and data gathered from a 5-point format can be readily transferred to 7-point equivalency using a simple rescaling method (Dawes, 2008) producing the same mean score. In the field of thermal comfort, probit and simple regression have been shown to have two important equivalences (Nicol *et al.,* 2012).

The rescaling process of the thermal sensation scale involved a two-step approach. Firstly, the extreme and middle categories of the 5-point scale were corresponded to the extremes and middle of the 7-point scale so that points ±2 become ±3 and 0 remains 0. The second step was to rescale points ±1. A simplified transformation would be the correspondence to points ±1.5 on the 7-point scale. This approach, however, assumes linearity between thermal sensation and the control variable (temperature) which - if not satisfied, e.g. due to measurement error or adaptation - may result in misleading findings (Nicol *et al.,* 2012).

Therefore, to rescale points ±1, the scale's interval property was investigated as to identify the relevant thermal distances between categories -2 and -1, -1 and 0, 0 and +1, +1 and +2, which in the linear approach would be equal to 1. For this purpose, logistic regression (with category +2 set as the reference category) and probit analysis were employed using air temperature (Tair), mean radiant temperature (Tmr) and globe temperature (Tglobe) as control variables.

To enable comparability, it was important to select indices available for all the studies. Correlation analysis of the RUROS data demonstrated that thermal sensation is better correlated with Tglobe ($r=0.68$, $p<0.01$) than with Tair ($r=0.63$, $p<0.01$) and Tmr ($r=0.62$, $p<0.01$). Globe temperature data however were available for only some of the indoor studies reviewed (Table 1). As a result, an operative temperature index was calculated for the RUROS data which could be tested as a control variable. The index was determined using the formula:

$$Top = [Tair * (10 * Vair)^{0.5} + Tmr] / [1 + (10 * Vair)^{0.5}]$$ (Humphreys *et al.*, 2015)

Where: Top is the operative temperature,
Tair represents air temperature,
Tmr is the mean radiant temperature (°C) and
Vair the wind velocity (m/s).

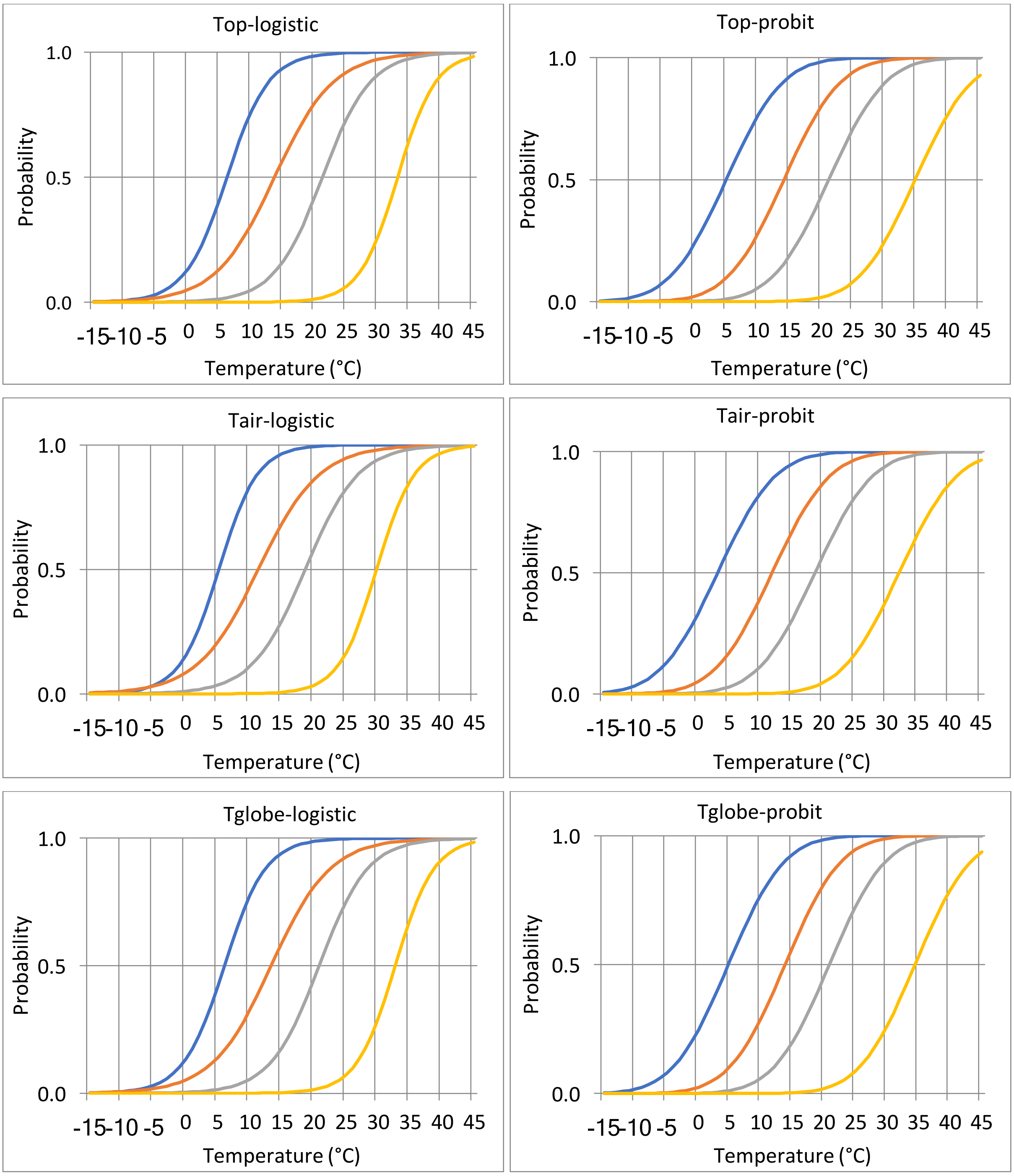
The results of the rescaling process for the different indices are presented in Figure 2 where the intersection between the sigmoid lines and the 0.5 line denote the logit/probit cut-off points, summarised in Table 2. These points correspond to a 50% percent probability of a vote change to the next category. Subsequently, the transformed scores of the (5-point scale) categories -1 and +1 were calculated from -3*(T[0] -T[-1])/(T[0] -T[-2]) and 3*(T[+1] - T[0])/(T[+1] -T[-1]) respectively, where T[-1] is the temperature cut-off point for "cool" sensation, T[0] for "neither cool nor warm", etc. Interestingly, the results revealed high consistency between the cut-off points (Table 2) as well as between the transformed points (Table 3) determined from the different control variables, and particularly between Top and Tglobe, which instilled further confidence for the selection of Top as the thermal index for the evaluation of comfort temperatures.

Table 2: Cut-off points for Top, Tair, Tglobe and Tmr derived from logistic regression and probit analysis.

	Logistic regression				Probit analysis			
Thermal sensation	Top 50%	Tair 50%	Tglobe 50%	Tmr 50%	Top 50%	Tair 50%	Tglobe 50%	Tmr 50%
Very cold	6.1	5.1	6.0	5.2	4.9	3.1	4.8	-0.1
Cool	13.6	11.3	13.3	16.0	14.0	11.8	13.8	15.9
Neither cool nor warm	21.1	18.6	20.8	28.2	21.1	18.6	20.8	28.6
Warm	33.0	29.8	32.7	59.0	34.8	32.0	34.4	54.3

Table 3. Transformation of 5-point scale ±1 categories to 7-point scale.

Method	5-point scale	7-point scale			
		Top	Tair	Tglobe	Tmr
Logistic regression	-1	-1.50	-1.62	-1.52	-1.59
	+1	1.84	1.82	1.84	2.15
Forced probit	-1	-1.31	-1.32	-1.31	-1.33
	+1	1.98	1.99	1.98	2.01



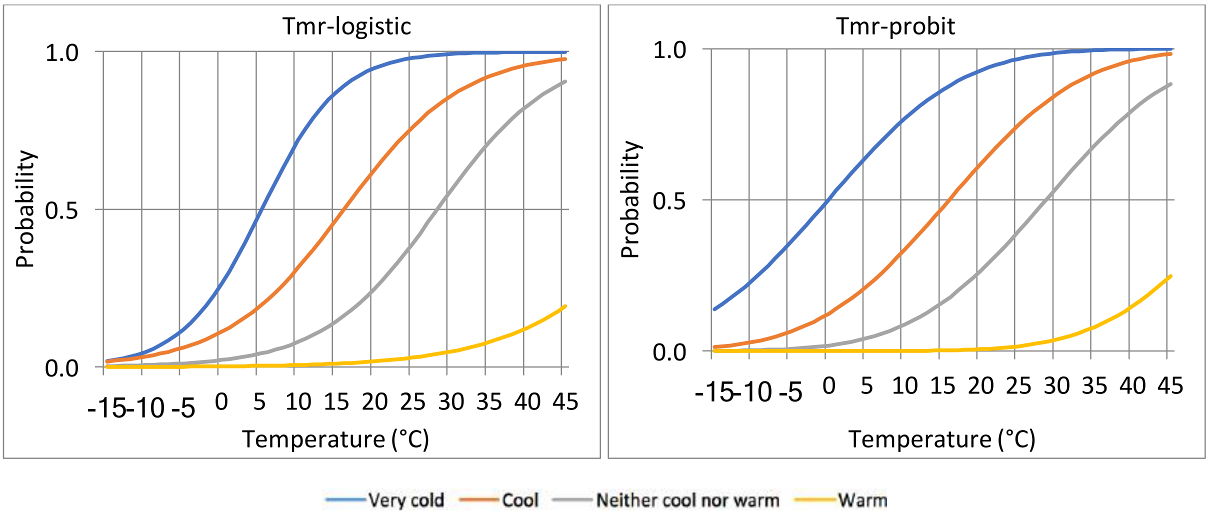


Figure 2: Logistic regression (left column) and probit analysis (right column) using Top, Tair, Tglobe and Tmr as control variables.

As shown in Figure 2, all the analysis for the transformation of the scales was done with both probit and logistic regression. This was due to the fact that the former method has been traditionally associated with the interpretation of data from field surveys in thermal comfort studies, while the latter, is being increasingly used for the analysis of thermal comfort surveys. The ease of use of logistic regression with modern statistical packages (as also highlighted by Nicol *et al.*, 2012), the more intuitive interpretation of its results, and the fact that the two methods provided very similar results led to the adoption of logistic regression results for the meta-analysis.

4. Meta-analysis

As the aim was to evaluate whether staff in airport terminals have comfort requirements closer to staff in offices, while passengers use the terminal as a transition area with more similarities to people found outdoors, it was necessary to separate the airport study in two distinct user groups, passengers and staff. The summary Table 4, shows that although the ratio of staff to passengers in the airports is roughly 1:5 in both seasons, nevertheless the sample is large enough to allow statistical analysis and comparable with the rest of the survey populations.

The data were analysed by means of the Statistical Package for Social Sciences (SPSS) and were initially subjected to quality checks to ensure high fidelity of the developed database totalling 6100 people.

Table 4: Cleaned up data on the sample of the population analysed for the different contexts.

	Airports Staff, HVAC	Airports Passengers, HVAC	Nicol, NV	Williams, NV	Williams, mixed	RUROS	Total
Summer	236	1188	875	148	n/a	1264	3711
Winter	229	1145	n/a	209	121	685	2389
Total	465	2333	875	357	121	1949	6100

A summary of the operative temperatures for the different studies at the different seasons is presented in Table 5. With the exception of the outdoor temperatures for RUROS, which demonstrate a large range and standard deviation, as would be expected for external conditions, the rest of the mean operative temperatures present a fairly uniform profile with a wider range of minimum and maximum temperatures for naturally ventilated buildings in the summer.

Table 5: Summary data for the operative temperature in the different studies

Study	Season	N	Top_min	Top_max	Top_mean	Std. Deviation
Airports Staff	summer	236	19.1	25.8	22.9	1.3
Nicol NV	summer	877	14.3	30.2	21.8	2
Williams NV	summer	167	16.6	25.9	21.9	1.7
Airports Passengers	summer	1188	19.4	26.3	22.8	1.3
RUROS	summer	1264	10.7	36.2	23.2	5.4
Airports Staff	winter	229	16.7	24.3	22.1	1.4
Williams NV	winter	209	18.6	25.9	21.9	1.5
Williams Mixed	winter	121	18.7	25.9	23.4	1.5
Airports Passengers	winter	1145	16.2	25.6	21.9	1.6
RUROS	winter	685	2.3	27.4	13.3	4.8

Following the transformation of the 5-point scale, analysis focused on understanding differences in thermal sensation and identifying the evidence of potential adaptive behaviour.

4.1. Clothing

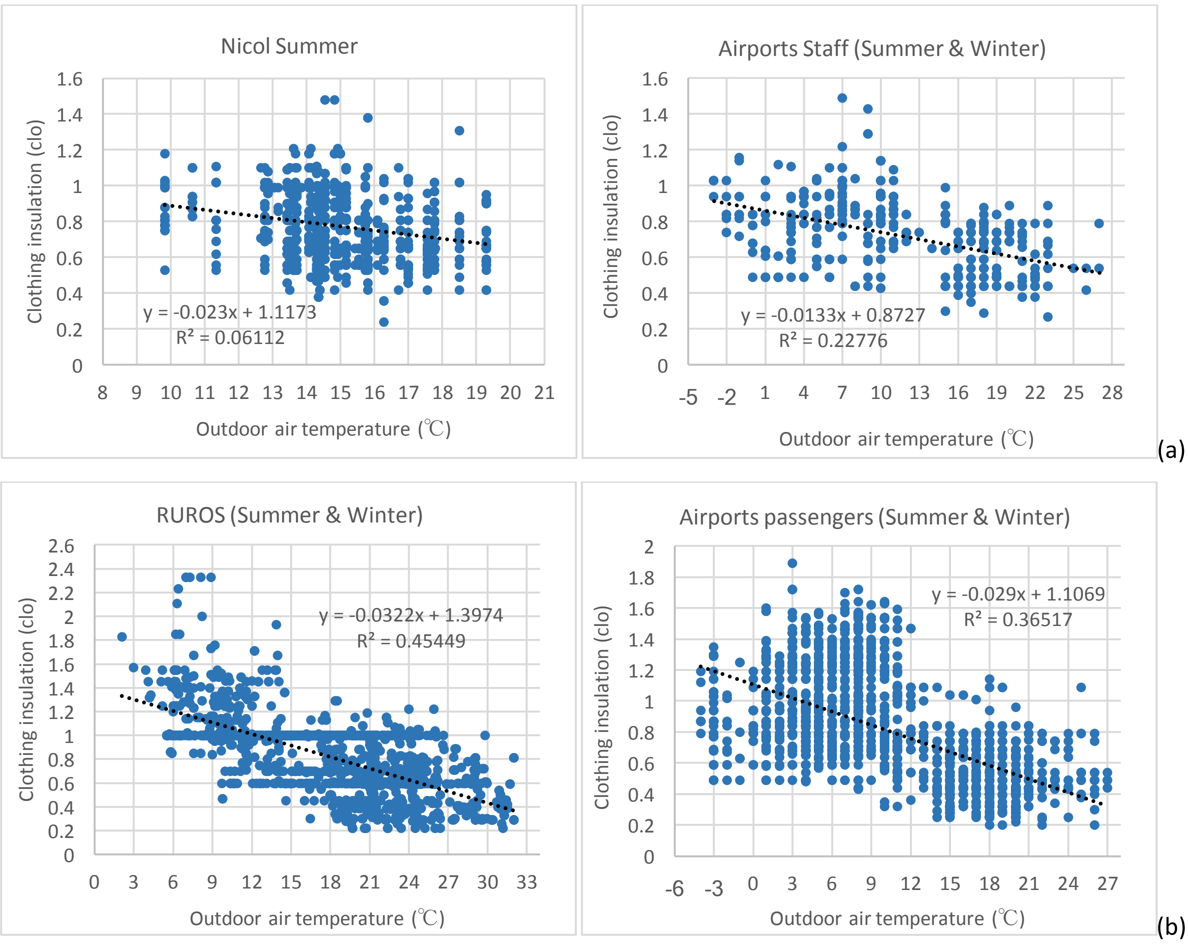


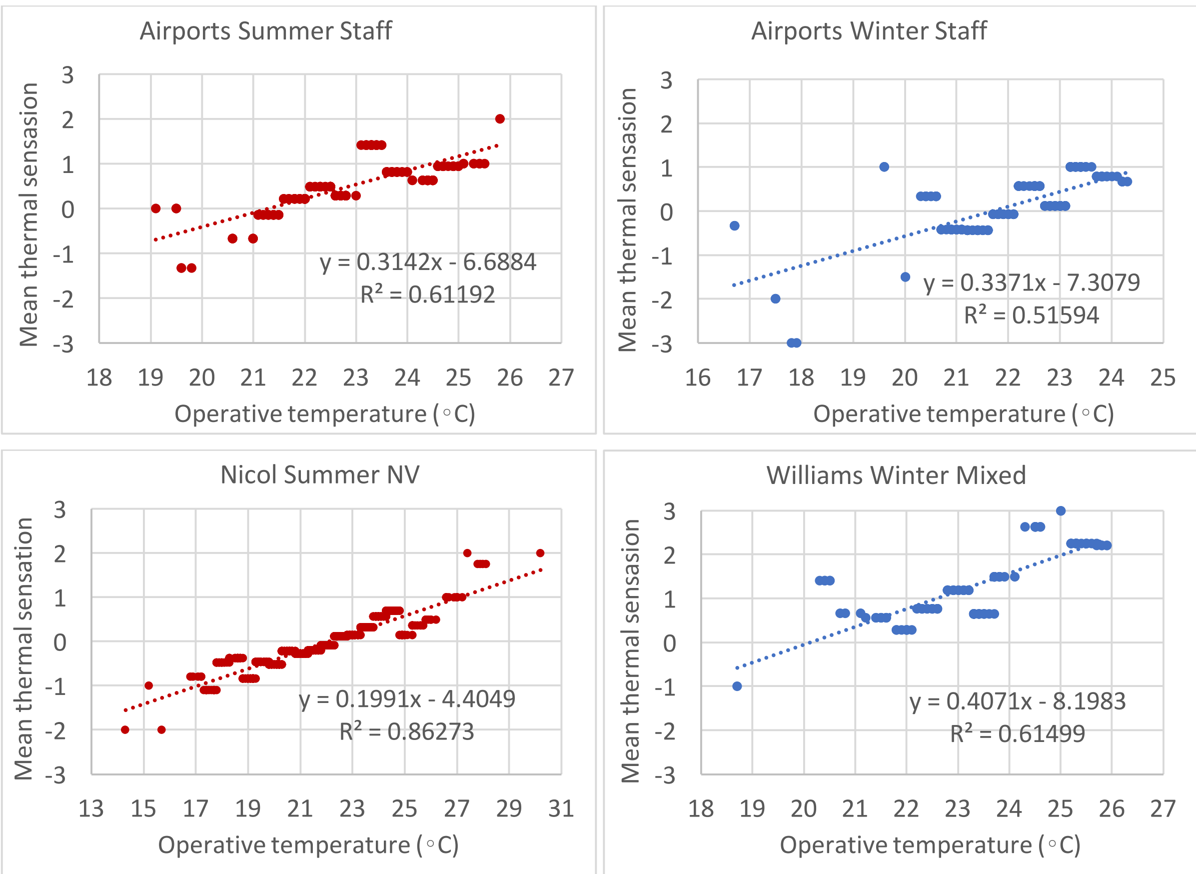
Figure 3: Clothing insulation as a function of outdoor air temperature for the different studies at different seasons, (a) for the staff-indoor group and (b) for the transition and outdoor group.

Considering clothing as a potential adaptive mechanism (Humphreys, 1977, 1979; Nikolopoulou and Lykoudis, 2016), clothing insulation levels were evaluated against outdoor air temperature. From the offices, only the Nicol study could be used. The data on external air temperature for Williams consisted of a fixed value per day, providing two external air temperatures for summer and another three for winter, which did not provide sufficient variation to inform the analysis.

The regression analysis of clothing insulation as a function or outdoor air temperature is presented in Figure 3. It is noticeable that passengers wear a wider range of clothing insulation, which is more comparable to clothing levels outdoors, with 37% and 46% of clothing varying along with external temperature at the two seasons. For airport staff, however, the clothing range worn is narrower, indicative of the set uniform for indoor conditions required in airports, more comparable to an office environment.

4.2. Neutral temperature

Neutral temperature, i.e. the temperature yielding a sensation of neither cold nor hot (Humphreys, 1976), was determined by means of weighted linear regressions using half-degree (°C) increments of operative temperature (de Dear *et al.*, 1997). The mean TS score was calculated for each bin and regression models were fitted between mean TS and operative temperature. Thermal neutrality was subsequently derived from solving the regression equations for TS = 0. The regression models were also used for the evaluation of the operative temperature ranges in which 80% and 90% of people would find the thermal conditions acceptable, in accordance to the statistical assumptions underlying the PMV/PPD heat-balance model (ISO 7730, 2005). All the parameters in the models, presented in Figure 4, achieved a statistical significance level of 99% or better.



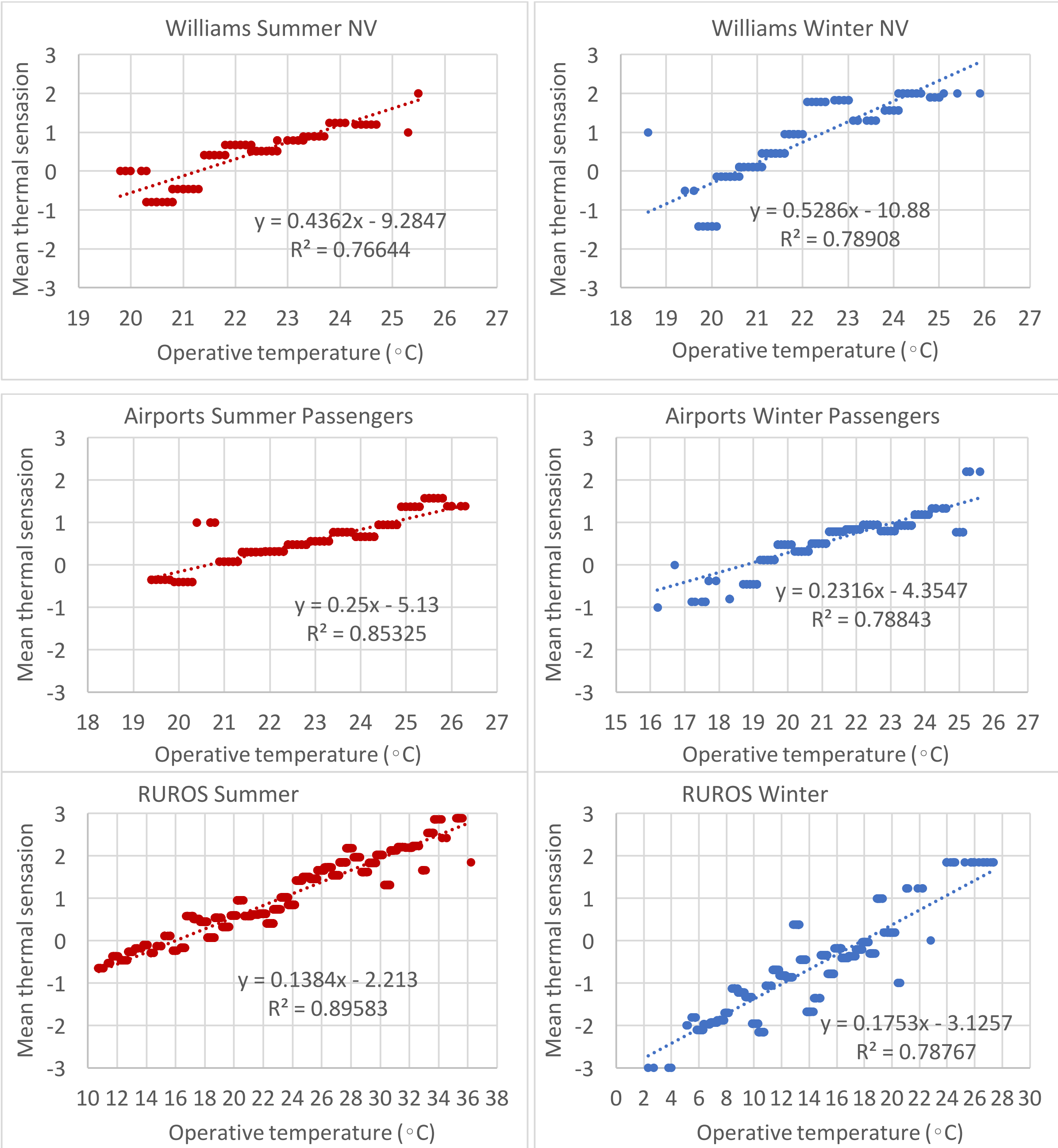


Figure 4: Mean thermal sensation as a function of operative temperature (°C) for the different studies

The analysis highlights a number of issues. Examining the slope of the equation as a measure of thermal sensitivity, it becomes apparent that in both winter and summer, airport passengers are less sensitive than the staff and more similar to the outdoor setting. A unit increase of passengers' TS would require a temperature rise of 4.0 °C in summer and 4.3 °C in winter, particularly comparable with 5.7 °C for outdoors in winter.

Airport staff, however, are more sensitive and closer to office staff. The temperature change required to alter airport staff's TS by 1 unit is nearly 3.0 °C for both seasons, similarly to office buildings where TS would not be altered with temperature changes below 3.7 °C in summer and 2.2 °C in winter.

Looking at neutral temperatures (Table 6), it becomes evident that Tn for airport staff is directly comparable to staff in offices in both seasons. For passengers, direct comparison with the outdoors is more difficult as airports are fully air-conditioned, and yet it is noticeable that in the summer Tn for passengers is lower than all office workers and airports staff, while in winter passenger's Tn is very close to Tn for the outdoor setting (at 18.8 °C and 17.8 °C respectively). In addition, the winter results derived from the evaluation of the 80% acceptability temperature ranges demonstrate a considerable similarity between the comfort zone for passengers and outdoor settings and particular tolerance to colder conditions (Table 6).

Table 6: Summary data for the neutral temperature in the different studies

Study	**Season**	**Building type**	**N**	**Slope**	**R^2**	**Tneutral (°C)**	**80% accept. (°C)**	**90% accept. (°C)**
Airports Staff	summer	HVAC	236	0.31	0.61	21.3	18.6-24.0	19.7-22.9
Nicol	summer	NV	875	0.20	0.86	22.1	17.9-26.4	19.6-24.6
Williams	summer	NV	148	0.44	0.77	21.3	19.3-23.2	20.1-22.4
Airports Passengers	summer	HVAC	1188	0.25	0.85	20.5	17.1-23.9	18.5-22.5
RUROS	summer	n/a	1264	0.14	0.90	16	9.8-22.1	12.4-19.6
Airports Staff	winter	HVAC	229	0.34	0.52	21.7	19.2-24.2	20.2-23.2
Williams	winter	NV	209	0.53	0.79	20.6	19.0-22.2	19.6-21.5
Williams	winter	Mixed	121	0.41	0.62	20.1	18.1-22.2	18.9-21.4
Airports Passengers	winter	HVAC	1145	0.23	0.79	18.8	15.1-22.5	16.6-21.0
RUROS	winter	n/a	685	0.18	0.79	17.8	13.0-22.7	15.0-20.7

5. Conclusions

As the results highlight, there is considerable difference in the adaptive capacity between the different groups analysed. The comfort temperatures for all employees, in the terminals and offices, are closer to the mean operative temperature (Tables 5-6), reflecting their long-term acclimatisation to the working thermal environment. On the other hand, passengers and people outdoors demonstrate wider adaptation capacity with a bigger difference between their mean operative and comfort temperature, while being less sensitive to these differences, as demonstrated by the low gradient of the respective equations for thermal sensation and neutral temperature.

In that respect, the paper succeeded in proving the hypothesis that the thermal comfort requirements of airport staff are closely compared to those of staff working in offices, as also found by the similar neutral temperatures for the two groups. However, the majority of the population in airport terminals is passengers, who inhabit the space as a transition space, more closely related to the comfort requirements of people using outdoor urban spaces, as the respective neutral temperatures highlighted. Once again, this brings to the forefront the important role of adaptation, both physical as well as behavioural and psychological, with experiences and expectations enabling the latter groups to achieve wider thermal comfort zones.

In fact, beyond the broad categories of different physical environments, it is the psychological adaptation that enables moving along the adaptive opportunity continuum, presented in Figure 1, based on the potential for adaptive capacity at a personal level, as manifested with the different groups at airport terminals. Further work in different climatic contexts and employing additional different databases could shed further light on the above, eliminating any implicit bias which may be inherent to specific datasets.

Such findings have important implications for energy use in buildings and particularly the high energy-consuming sector of airport terminals. From introduction of soft policies to address flexibility in clothing for staff uniforms, to the design of localised building services for staff rather than treating large volumes of air in terminals, it becomes apparent that thermal comfort surveys continue to play an important role not only for research but also for understanding human behaviour and ultimately improvements to the design of the built environment.

Finally, the work has shed some light on the technique of potential transformation of thermal comfort scales. The last 15 years have witnessed an increased amount of outdoor thermal comfort surveys, many of which have used a variety of thermal sensation scales from five-point (Nikolopoulou *et al.*, 2001; Nikolopoulou and Lykoudis, 2006; Aljawabra and Nikolopoulou, 2010; Nikolopoulou *et al.*, 2011) to nine-point (Kántor *et al.*, 2016). The paper identified possibilities for eventual comparison of such work from different geographical, climatic and socio-cultural contexts that will inform the wider debate on thermal comfort further.

6. References

Aljawabra, F. and Nikolopoulou, M., 2010. The influence of hot arid climate on the use of outdoor urban spaces and thermal comfort: do cultural and social backgrounds matter?, Intelligent Buildings International, Vol. 2, No. 3, pp. 198-217.

ANSI/ASHRAE Standard 55-2004. *Thermal Environmental Conditions for Human Occupancy*.

Colman, A.M. and Norris, C.E., 1997. Comparing rating scales of different lengths: Equivalence of scores from 5-point and 7-point scales, *Psychological Reports*, Vol.80, pp. 355-362.

Dawes, J., 2008. Do data characteristics change according to the number of scale points used? An experiment using 5-point, 7-point and 10-point scales, *International Journal of Market Research*, Vol. 50, No. 1, pp. 61–104.

de Dear, R.J., Brager, G.S. and Cooper, D., 1997. *Developing an Adaptive Model of Thermal Comfort and Preference,* Final Report on ASHRAE RP-884.

Fanger, P.O., 1970. Thermal Comfort., Danish Technical Press, Copenhagen.

Humphreys, M.A., 1979. The influence of season and ambient temperature on human clothing behaviour. In (eds.) P.O. Fanger and O. Valbjorn Indoor Climate: *Proc. of the first International Climate Symposium*, Copenhagen, 1978, Danish Building Research Institution, Copenhagen.

Humphreys, M.A., 1977. Clothing and the outdoor microclimate in summer, *Building and Environment*, Vol. 12, pp. 137-142.

Humphreys, M.A., 1976. Field studies of thermal comfort compared and applied, *J. Inst. Heat. & Vent. Eng*, 44, pp. 5-27.

Humphreys, M., Nicol, F. and Nikolopoulou, M., 2015. Environmental criteria for design, *Guide A: Environmental Design*, Chartered Institute of Building Services Engineers, CIBSE, London.

ISO 7730, 2005. *Ergonomics of the Thermal Environment - Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*.

Kántor, N., Kovács, A., Takács, Á., 2016. Seasonal differences in the subjective assessment of outdoor thermal conditions and the impact of analysis techniques on the obtained results, *International Journal of Biometeoroly,* Vol. 60, No. 11, pp 1615–1635.

Kotopouleas, A. and Nikolopoulou, M., 2016. Thermal comfort conditions in airport terminals: Indoor or transition spaces? *Building and Environment,* Vol. 99, pp. 184-199.

Kotopouleas, A. and Nikolopoulou, M., 2018. Evaluation of comfort conditions in airport terminal buildings, *Building and Environment,* Vol. 130, pp. 162-178.

Nicol, F., Humphreys, M. and Roaf, S., 2012. *Adaptive Thermal Comfort: Principles and Practice,* Routledge.

Nikolopoulou, M., 2004. Outdoor Thermal Comfort. In (eds.) K. Steemers & M.A. Steane, *Architecture and Variety: Environmental Perspectives,* Spon Press, pp. 101-119.

Nikolopoulou, M., 1998. *Thermal Comfort in Outdoor Urban Spaces*, PhD thesis, University of Cambridge (unpublished).

Nikolopoulou, M., Baker, N. and Steemers, K., 2001. Thermal comfort in outdoor urban spaces: the human parameter, *Solar Energy*, Vol. 70, No. 3, pp. 227-235.

Nikolopoulou, M., Kleissl, J., Linden, P.F. and Lykoudis, S., 2011. Pedestrians' perception of environmental stimuli through field surveys: Focus on particulate pollution. *Science of The Total Environment*, Vol. 409, No. 13, pp. 2493-2502.

Nikolopoulou, M. and Lykoudis, S., 2006. Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Building and Environment*, Vol. 41, pp. 1455-1470.

Nikolopoulou, M. and Steemers K., 2003.Thermal comfort and psychological adaptation as a guide for designing urban spaces, *Energy and Buildings*, Vol. 35, No. 1, 95-101.

Spagnolo, S. and de Dear, R.,2003. A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia, *Building and Environment*, Vol. 38, pp.721-738.

Acknowledgements

The availability of the datasets has been pivotal for enabling such analysis. These include:
[1] Indoor Offices: ASHRAE RP-884 Adaptive Model Project - Data Downloader
http://sydney.edu.au/architecture/staff/homepage/richard_de_dear/ashrae_rp-884.shtml
[2] Outdoor urban spaces: EU FP5 project RUROS (Rediscovering the Urban realm and Open Spaces) databasehttp://alpha.cres.gr/ruros , EVK4-CT2001-00032.
[3] Airport terminals: EPSRC project "Integration of active and passive indoor thermal environment control systems to minimize the carbon footprint of airport terminal buildings", EP/H004181/1.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Thermal comfort in dwellings in the subtropical highlands – Case study in the Ecuadorian Andes

Isabel Mino-Rodriguez[1], Ivan Korolija[1] and Hector Altamirano[1]

[1] UCL Institute for Environmental Design and Engineering, 14 Upper Woburn Place, London WC1H 0NN, isabelmino.16@ucl.ac.uk

Abstract: Thermal comfort in dwellings located in different weather conditions have been largely studied. The indoor environmental criteria have been well defined for mechanically conditioned buildings in mid-latitudes and naturally ventilated spaces in the subtropics. The subtropics are known for being hot-humid environments at low altitude. However, the highlands in the tropics have a subtropical-highland climate characterised by narrow annual temperature oscillation, noticeable diurnal temperature variation and high levels of solar radiation and precipitation due to its latitude and altitude. Field thermal comfort studies in housing in the Highlands reveals up to a 90% of user's satisfaction to temperature below 18°C. Indoor temperatures in dwellings in the Andes highlands can be even lower than 18°C as buildings are uninsulated and operate under free-running conditions throughout the year. This study seeks to identify the thermal comfort range and the difference in residents' perception of inhabitants living between 2300 m and 3100 m above sea level, in the Andes highlands. 195 thermal comfort votes were collected during the dry season. Results show that people living in the high-altitude are more sensitive to draught and prefer lower temperatures (16°C – 24°C), while inhabitants living in the low-altitude find temperatures above 26°C pleasant and prefer higher air movement.

Keywords: Thermal comfort, adaptive model, residential buildings, high altitude, subtropical highlands

1. Introduction

Subtropical highlands are a mountainous region that extends at the east, south-eastern Africa, Central and South America, across South Asia and in few areas of Australia (Figure 1). The higher mountains range in the tropics are in Central and South America and host large cities such as Bogota (2600m – capital of Colombia), Quito (2800m – capital of Ecuador), and La Paz (3640m – capital of Bolivia). The key characteristics of the subtropical climate in the Northern Andes (Ecuador, Colombia and North of Peru) are a narrow annual temperature oscillation, noticeable diurnal temperature variation and high levels of solar radiation and precipitation due to its latitude and altitude. As the altitude above sea level increases, the temperature, atmospheric pressure, and humidity decrease while the levels of solar irradiance and precipitation increase.

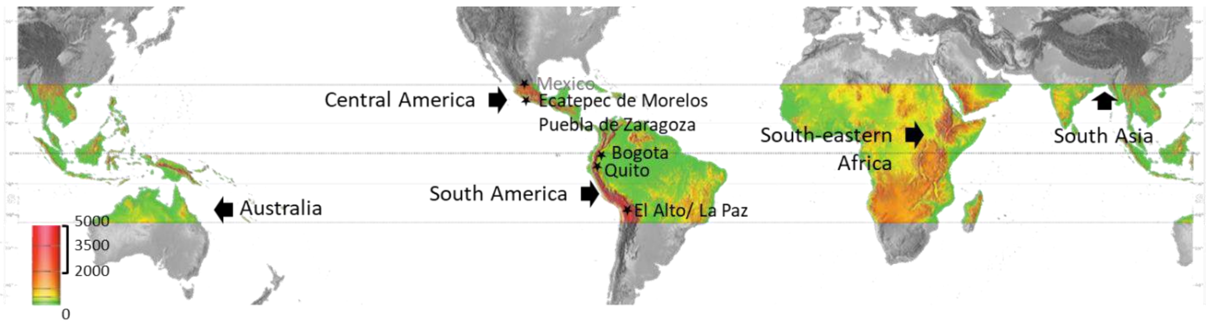


Figure 1: Topography of the Tropics (Amante and Eakins, 2009)

Few thermal comfort studies have been conducted to understand the subjective thermal perception at different altitudes. Field work on indoor thermal conditions in mid and high-altitude regions have been conducted mainly in Nepal (Rijal and Yoshida, 2006; Fuller, Zahnd and Thakuri, 2009; Rijal, Yoshida and Umemiya, 2010) and China (Huang et al., 2016). Findings reveal high satisfaction rate of residents to low indoor operative temperatures, as show in Table 1. At mid altitude zones in Nepal, the mean neutral temperature derived from regions with cool climate at 2600m is lower than temperatures derived for lower regions with temperate weather conditions (Rijal, Yoshida and Umemiya, 2010). At higher altitude as in Lhasa, located in the Tibetan Plateau at 3,650m, a neutral temperature of 18.9°C for summer and 23.3°C in winter was reported (Yang et al., 2013). The results highlight that, despite the low indoor temperature, over 90% of the users reported to be satisfied with the indoor thermal environment. At Lomangtang, an area located at Mustang District in Nepal at 3,705m above sea level, a low mean neutral temperature (10.7°C) was reported (Rijal and Yoshida, 2006). Opposite to the high value of clothing described of 5.96clo for females and 2.87clo for males. The adaptation to low-pressure environment and the psychological and behavioural patterns may explain the difference on thermal comfort sensation of occupants (Yang *et al.*, 2013; Yan *et al.*, 2014). The main behavioural adaptation of residents in the Tibetan Plateau are wearing warming clothes including "wearing socks and shoes", changing rooms and dietary custom based on high-calorie and high-protein meals (Rijal, Yoshida and Umemiya, 2010; Yang *et al.*, 2013; Yan *et al.*, 2014). Moreover, the psychological behaviour may include particular ethnics and regional differences, cultural and behavioural aspects, and user's thermal history (ISO, 2005; Forgiarini Rupp, Vásquez Giraldo and Lamberts, 2015). Worth mentioning is that low humidity levels do not have an adverse impact on thermal comfort satisfaction whereas the predominant variable is the indoor temperature (Huang et al., 2016).

Table 1: Summary of outdoor and indoor conditions from previous studies

AREA OF STUDY	Altitude[(a)]	Season	Tout[(b)]	Tn	Tgm[(c)]	Tgmn	Reference
Bhaktapur Nepal	1350 m	Summer	22.2	25.6	26.4	26.3	(Rijal, Yoshida and Umemiya, 2010)
		Winter	10.6	15.2	13.4	13.9	
Dhading Nepal	1500 m	Summer	25.4	29.1	30.0	29.3	(Rijal, Yoshida and Umemiya, 2010)
		Winter	13.3	24.2	23.8	24.3	
Kaski Nepal	1700 m	Summer	18.8	23.4	23.2	23.2	(Rijal, Yoshida and Umemiya, 2010)
		Winter	9.8	18.0	17.0	17.2	
Solukhumbu Nepal	2600 m	Summer	13.1	21.1	21.3	21.4	(Rijal, Yoshida and Umemiya, 2010)
		Winter	4.0	13.4	12.1	12.4	
Lhasa China	3650 m	Summer	16.4	23.3	22.0	-	(Yang et al., 2013)
		Winter	-1.5	18.9	11.0	-	
Lomangtang Nepal	3705 m	Winter	-1.3	10.7	7.8	9.0	(Rijal and Yoshida, 2006)

(a) Approximated value

(b) Monthly mean outdoor air temperature (Summer-May/Winter-Jan)

(c) Mean globe temperature when voting & voting for neutral

On the other hand, experimental studies carried out in a decompression chamber demonstrate that the convective and evaporative heat exchange between the human skin surface and the environment could be affected at hypobaric conditions (low air-pressure conditions) (Ohno et al., 1991). At low ambient pressure, the evaporative heat transfer increases whereas loss of heat by convection decreases (Ohno et al., 1991; Wang et al., 2010). These changes in heat transfer, may cause changes in blood flow and consequently modify the body heat loss affecting people's thermal comfort sensation (Ohno et al., 1991; Wang et al., 2010). Under moderate hypobaric conditions at 2300 meters above sea level, the mean thermal sensation drops, people tended to feel cooler and were more sensitive to draught (Wang et al., 2010). The adaptation of residents to a specific context should be considered when defining thermal comfort criteria for non-conditioned buildings. The existing standards are intended to provide input for the design and assessment of acceptable indoor environments in mechanically conditioned buildings and naturally ventilated buildings. The adaptation of local inhabitants to cold and hypobaric environment may lead to differences in the perception of the indoor environment. Therefore, the implementation of these standards may not address the requirements of highlands residents and may change and the way buildings are designed as well as occupant's expectations.

To date, little research has been conducted to assess the thermal performance of unconditioned dwellings located in the highlands and even fewer in subtropical highlands. The objective of this work was to conduct thermal comfort field studies in residential buildings located at different altitudes in the Ecuadorian Andes in Quito.

2. Geography and climate characteristics of Quito

Under Köppen climate classification, Quito has a subtropical highland climate (Cfb) (Peel, Finlayson and McMahon, 2007). Due to its altitude and location close to the equator, the annual temperature variation is narrow (Figure 2). The maximum annual difference of the length of the daytime is approximately 30 minutes, thus the length on its own has no great impact on the climate, but it does affect the solar irradiance (Emck, 2007).The estimated global solar irradiation in Ecuador is 4,575 Wh/m2/day (CONELEC and CIE, 2008) while the precipitation levels varies between 800 to 1,500 mm per year.

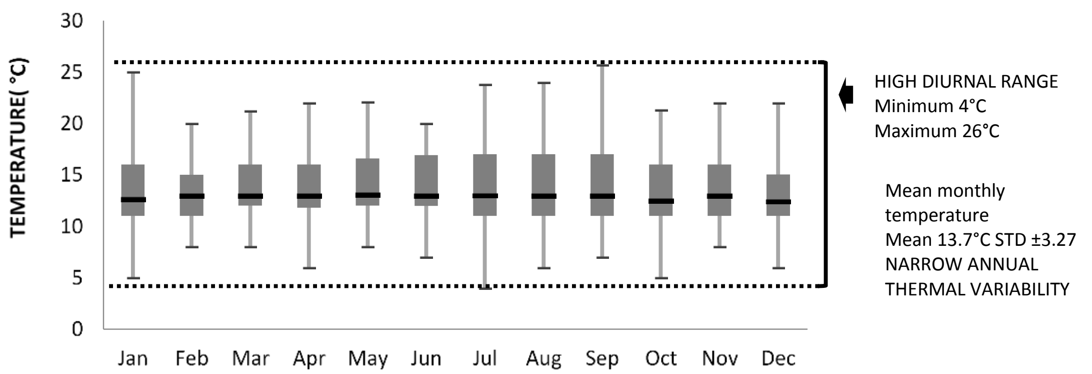


Figure 2: Quito Dry-bulb temperature (°C) – Source: NREL

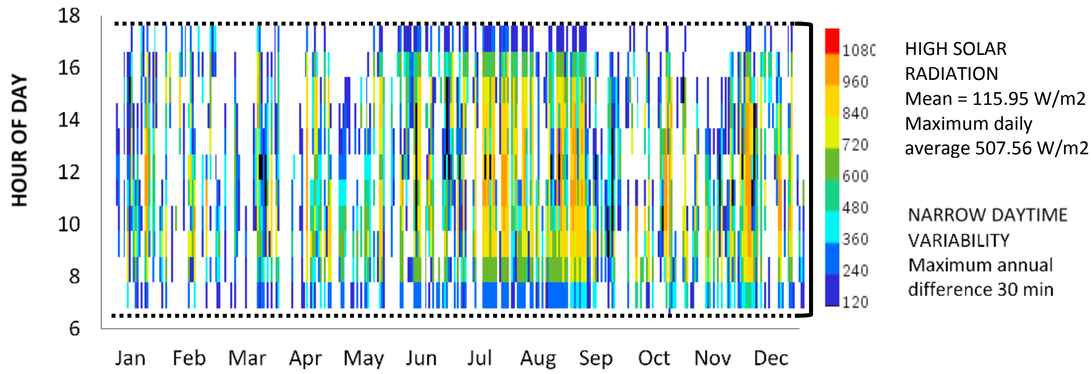


Figure 3: Quito global normal radiation (W/m2) – Source: NREL

Three locations nearby Quito were selected for this study as shown in Figure 4. The constraints for the selection of the zone studies were a) availability of meteorological data, b) altitude range and c) similarity of weather conditions. It is recommended that the weather station is be located within 30 – 50 km and ±100 m of altitude from a weather station (NREL, 2016). Hourly weather data is available from nine automatic meteorological stations located in the Metropolitan District of Quito (DMQ) within a radius of 20 km and in the same drainage basin and mountain slope so the weather conditions are similar. The altitude range where the stations are located goes from 2330 meters to 3066 meters above sea level. Thus, three locations were selected at different altitude range. A low zone (Tumbaco) located between 2300 to 2400 meters above sea level, the mid zone (Calderon) between 2600 m to 2700m and a high zone (Cutuglahua) range between 3000 m to 3100 m. The parish boundaries were the limit area for the surveys' implementation, as well as a ± 50-meter altitude difference from the meteorological station.

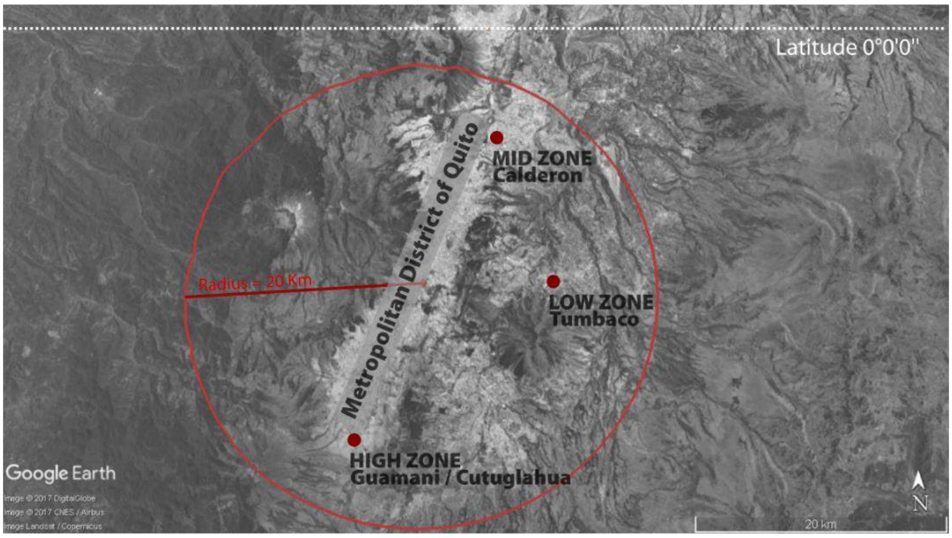


Figure 4: Location of three zone studies, the low zone (2300 – 2400 m), the mid zone (2600 -2700m) and the high zone (3000 - 3100)

3. Thermal comfort survey

The field study was conducted for 21 days between September and November 2017. A total of 195 individuals were interviewed in 138 dwellings. The subjective questionnaire includes questions about general background such as age, gender, weight and height. Occupants were also asked to provide information on clothing and previous activity the participants where developing. "Right here, right now" thermal comfort questions were administered to gather subjective responses about environmental sensation, preference and acceptability regarding temperature, humidity and air movement. The ASHRAE seven-point thermal sensation scale was adopted for this survey to quantify thermal sensation (ISO, 2007). The seven-degree two pole scale was also extended to assess the occupants' humidity perception (Yang et al., 2013) (Table 2) and the occupant's preference on humidity and air movement (Table 3). The questions and scales were translated and validated to Spanish. The scales were composed of single term with adverbs to modulate (ISO, 2007). There are few reference in the literature regarding the translation to Spanish of the wording used for the different scales (Hidalgo and Zavala, 2007; Llaneza, 2008; Castilla *et al.*, 2010; Gomez, Morales and Torres, 2011). Therefore, seven bilinguals (Spanish – English) building scientist and a local sociologist validate the translation. In addition, the questionnaire was tested previous implementation among a group of residents to verify the understanding of the content.

Table 2: The 7-point sensation scale adopted in the questionnaire

SENSATION	-3	-2	-1	0	+1	+2	+3
Thermal	Muy frío	Frío	Ligeramente frío	Ni caliente, ni frío	Ligeramente caliente	Caliente	Muy caliente
	Cold	*Cool*	*Slightly cool*	*Neither warm, nor cool*	*Slightly warm*	*Warm*	*Hot*
Humidity	Muy seco	Seco	Ligeramente seco	Ni húmedo, ni seco	Ligeramente húmedo	Húmedo	Muy húmedo
	Very dry	*Dry*	*Slightly dry*	*Neither hot, nor warm*	*Slightly humid*	*Humid*	*Very humid*

The research design is a transverse survey where each participant gave just one response during the survey period. A maximum of three thermal comfort surveys were collected at each home. On average five surveys were conducted per day between 8:00 am and 6:00 pm. For the survey campaigns, two research assistants accompanied the field investigator. The team randomly approached to different dwelling and asked the occupiers to participate in the survey. Door to door technique was mainly used to gain access to potential participants. The questionnaire was designed in a way that participants will have time to adapt to the environment before answering. Participants were engaged in nearly sedentary activity for about 20 minutes before answering the questions about indoor environment perception. The interviews were conducted by the same researcher and the answers were taken orally and recorded in a paper form. Show cards containing the different rating scales were used to facilitate respondents' answer. Simultaneous measurement of the indoor climatic parameter - air temperature, globe temperature, relative humidity and air velocity - were recorded by a second researcher. A heat stress monitor was positioned at 0.6 m height from the finished floor and approximately 0.5 m from the occupant.

Table 3: The seven-point perception scale adopted in the questionnaire

PREFERENCE	-3	-2	-1	0	+1	+2	+3
Thermal	Mucho más frío	Más frío	Ligeramente más frío	Sin cambio	Ligeramente más caliente	Más caliente	Mucho más caliente
	Much cooler	*Cooler*	*Slightly cooler*	*No change*	*Slightly warmer*	*Warmer*	*Much warmer*
Humidity	Muy más seco	Más seco	Ligeramente más seco	Sin cambio	Ligeramente más húmedo	Más húmedo	Mucho más húmedo
	Much drier	*Drier*	*Slightly drier*	*No change*	*Slightly more humid*	*More humid*	*Much more humid*
Air movement	Mucho menos aire	Menos aire	Un poco menos aire	Sin cambio	Un poco más aire	Más aire	Mucho más aire
	Much less air movement	*Less air movement*	*A bit less air movement*	*No change*	*A bit more movement*	*More air movement*	*Much more air movement*

Hourly meteorological data corresponding to dry bulb temperature, relative humidity, solar radiation and precipitation were obtained from September to November 2017 (Secretaria del ambiente Quito, 2004). Table 4 presents a statistical summary of weather data from the survey period. Due to the altitude difference, air temperature varies 1.4°C between the mean temperature of the low and mid zone and a 2.4°C between the mid zone and high zone. The largest outdoor temperature oscillation recorded was due to diurnal variation rather than monthly changes. Above 12.9°C is the diurnal oscillation observed in the three zones, the lower zone has the higher diurnal oscillation of 18.1°C and the mid zone presents a diurnal oscillation of 13.7°C. High levels of outdoor relative humidity are observed, the mean value of relative humidity within the three zones is 72%. The higher accumulation of global solar radiation within the period of the study is observed in the mid zone and low zone. Despite the assessment period correspond to the dry season, disperse precipitation levels were recorded within the study period, presenting the higher levels in the high zone.

Table 4: Statistical summary of weather data (12th September – 12th November)

ZONES	Low zone	Mid zone	High zone	Low zone	Mid zone	High zone
		Air temperature (°C)			**Relative Humidity (%)**	
Mean	16.4	15.0	12.6	71	73	71
SD	4.3	3.4	3.1	20	19	17
Max	26.9	23.6	20.8	97	100	99
Min	8.8	9.9	7.9	20	21	23
		Solar Radiation (W/m^2)			**Precipitation (mm)**	
Mean	235.4	241.7	207.4	0.1	0.1	0.2
SD	337.9	335.1	298.3	1.2	0.8	1.1
Max	1191.8	1181.3	1084.1	30.6	18.3	21.4
Sum	299471.5	307407.9	263848.5	154.7	128.5	207.0

4. Analysis

4.1. Description of occupants

187 out of 195 surveys were considered valid for analysis, as answers correspond to respondents aged between 18 years-old and 65 years-old. Eight surveys were not considered for the data analysis as the age range surpasses the established range. The respondents' average height, weight and estimation of the body surface area (BSA) is summarised in Table 5. The BSA in this study was calculated from the participants actual height and weight through the Mosteller' formula, which is recommended due to its simplicity and suitability (Vebraecken *et al.*, 2006). The standards considered as an average individual, a man weighing 70kg and 1,75m tall (BSA 1.8 m^2) and a women weighing 60 kg and 1,70 m tall (BSA 1,6m^2) for the metabolic rate tables and data (ISO, 2004). The mean calculated BSA value is close to the one used for the standards.

Table 5: Summary of participants' general background information

	Sample size (n)		**Height (cm)**		**Weight (kg)**		**Body surface area (BSA) (m^2)**	
	Male	Female	Male	Female	Male	Female	Male	Female
Low zone	28	34	167	153	69	65	1.79	1.65
Mid zone	25	38	169	157	73	67	1.84	1.70
High zone	22	40	164	153	70	65	1.77	1.66
Total	**75**	**112**	**167**	**154**	**71**	**66**	**1.80**	**1.67**

4.2. Metabolic rate (MET)

People's activity often consists of a mixture of activities. Thus, a time-weighted average metabolic rate was calculated for the individuals' due to variation on activity within a period of one hour or less (ASHRAE, 2009). A correction according to the calculated BSA was applied despite the mean calculated BSA is similar to the one used in the ISO standards (ISO, 2004). The sample size is not significant to represent the whole population thus the metabolic rate was adjusted to each subject. The metabolic rate of the participants for a one-hour period varied between 0.8 met to 2.1 met with an average of 1.3 met (±0.3) denoting the wide range of activities at home. Only 25% of participants were engaged in light activities (below 1.00 met) while 45% were engaged in heavier activities (above 1.3 met). At the time of the survey, the respondents were engaged in near-sedentary physical activities, with metabolic rates ranging from 60 to 70 W/m^2. Thus, the metabolic rate for 30 minutes period varied between 0.8 met to 1.6 met with an average of 1.1 met (±0.1).

4.3. Clothing insulation (Clo)

Clothing insulation is an important variable to be investigated in dwellings as occupants would have much more flexibility to adjust their clothing compare to places where a certain dress code is required. The method used to estimate the clothing insulation level was garment by garment accounting for the chair insulation (Dear et al., 1998). Individual's clo was calculated based on the information given by participants and the clo values provided in ASHRAE Standard 55-2010 (ASHRAE, 2010). Clothing insulation was analysed by gender, day time and thermal comfort votes. The mean value of clothing insulation varied from 0.53 clo to 0.70 clo in the high zone (Table 6). Clo difference according to daytime can be observed in the high zone, the mean clo in the morning is 0.66 while the average in the afternoon is 0.73. Females in the low and high region have a lower clothing insulation than males. This trend is not followed by inhabitants in the mid zone.

Table 6: Clothing insulation by gender and day time

		Low zone			**Mid zone**			**High zone**			
	Unit	Female	Male	Mean	Female	Male	Mean	Female	Male	Mean	Mean by day time
Morning	(clo)	0.52	0.55	0.53	0.63	0.53	0.59	0.66	0.67	0.66	0.60
Afternoon	(clo)	0.49	0.58	0.53	0.62	0.58	0.60	0.71	0.77	0.73	0.62
Mean by zone	(clo)	0.50	0.57	0.53	0.62	0.55	0.60	0.68	0.73	0.70	0.61
SD				0.14			0.16			0.21	
Min				0.33			0.27			0.33	
Max				1.00			1.10			1.23	

A reduced level on the clothing insulation is noticed as the thermal sensation votes drop from cool to warm despite the altitude of each zone (Figure 5). At the warm vote point, the mean clo level is 0.48 while at the cool vote point it is 0.71 clo. The clothing difference for participants voting cool is 0.1 clo between the high and the low zone. That difference is consistent among all the votes. At the neutral vote point, the clothing mean value is 0.52 clo, 0,63 clo and 0,67 clo for the low, mid and high zones respectively. This variation on clothing insulation values indicate, to a certain degree, some behavioural adaptation in response to the variations of the indoor air temperature as in Yang (Yang et al., 2013).

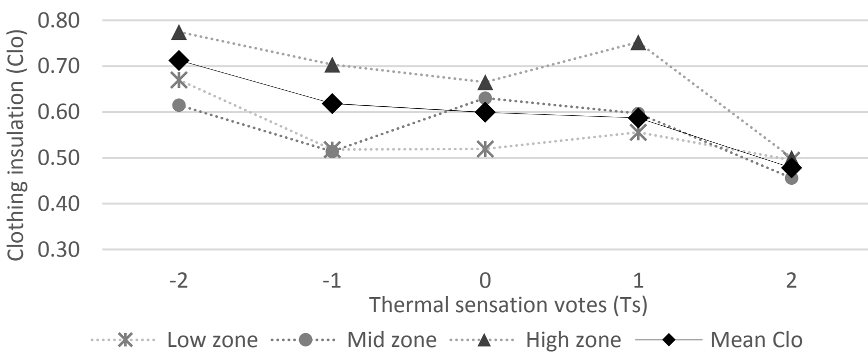


Figure 5: Clothing insulation according to thermal sensation votes (Ts)

5. Indoor environmental conditions

The scatter diagram of indoor conditions illustrated in Figure 6 clearly shows that the indoor conditions in the high zone are concentrated at operative temperature lower than 20°C and indoor relative humidity higher than 50%. Whereas the indoor conditions in the low zone are concentrated at operative temperature higher than 24°C and relative humidity lower than 45%. The maximum indoor relative humidity is 73%, while the lower is 29%.

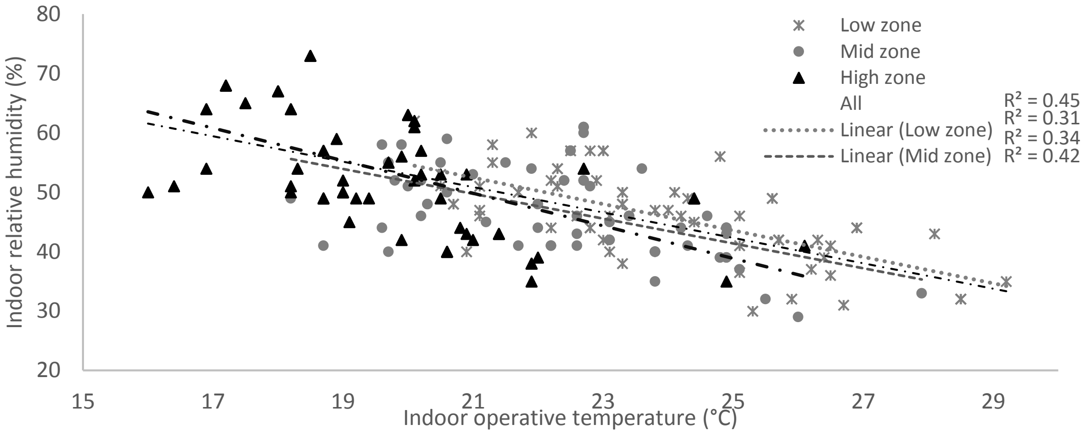


Figure 6: Scatter diagram of indoor conditions

The frequency of occurrence of the indoor operative temperature is presented in Figure 7. The mean operative temperature in dwellings located in the low zone is 23.6°C (±2.1), in the mid zone 22.5°C (±2.0) and in the high zone 19.8°C (±2.1). The mean Top varies 4°C, between the high zone and the low zone. Compared with the mean outdoor temperature calculated from 8:00 am to 18:00 pm, the variation is of 3.5°C in the low zone and 4.5°C in the mid and high zone.

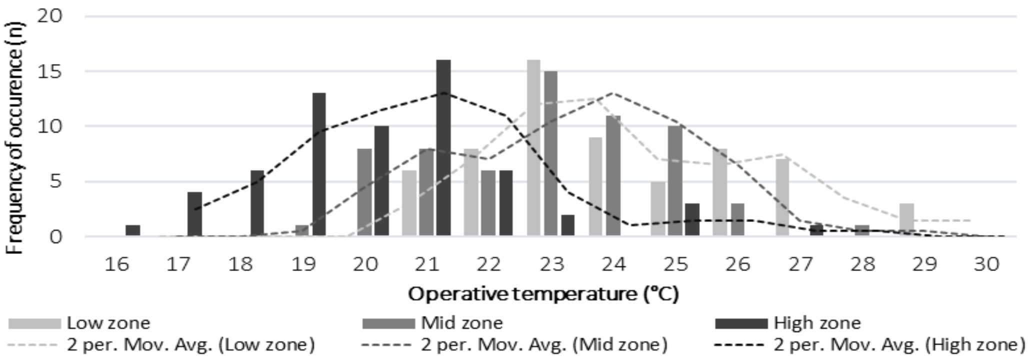


Figure 7: Distribution of the operative temperature

6. Subjective feeling and perception

The sensation, preference and satisfaction votes collected from the participants were analysed. The frequency distribution of thermal sensation and thermal preference votes is shown in Figure 8. A person can be considered to be comfortable when the thermal sensation votes is 'slightly cool' (-1), 'neutral' (0) or 'slightly warm' (+1) on the ASHRAE scale (Nicol and Humphreys, 2010). Therefore, over 80% of the total respondents are in comfort. The higher percentage of neutral votes (90%) is observed in the low zone. The opposite trend was observed among the respondents in the higher zone that have the lower percentage of comfort of the survey (74%). The mean judgement of resident is close to the thermal neutrality being 0.16 in the low zone, 0.02 in the mid zone -and -0.65 in the high zone. Only

37% of the respondents in the high zone would prefer to keep the same temperature in the survey as show in Figure 8. As in previous studies, an increased threshold for cold sensation is observed in residents living above 3,000 m. 61% of participants in the high zone would prefer the indoor operative temperature to be slightly warmer (52%) warmer (8%) and much warmer (1%). Opposite to residents in the low zone where 61% of the participants would prefer slightly cooler (52%) or cooler environments (8%). The highest rate to maintain the same indoor operative temperature is observed in the mid zone (70%).

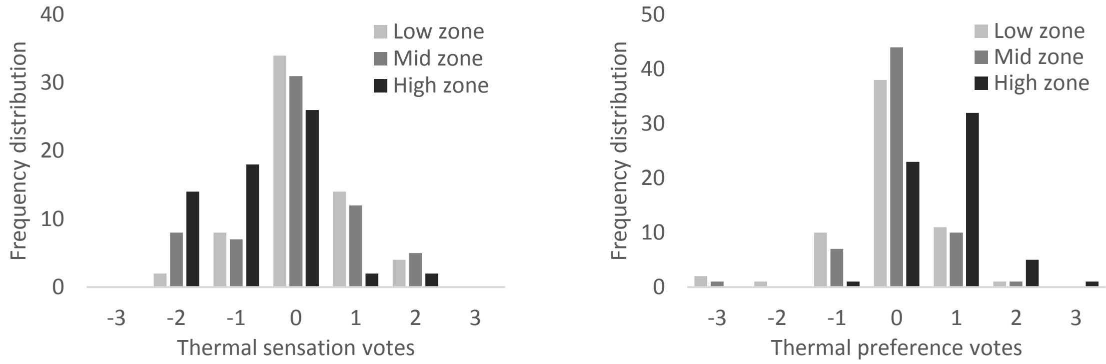


Figure 8: Distribution of thermal sensation and thermal preference votes

As for preference votes, Figure 9 shows the distribution of preference votes for relative humidity and indoor air movement. A high percentage of the participants (60%) prefer no change in the indoor relative humidity. These votes are consistent with the indoor environment measurement that shows a mean indoor relative humidity of 50%. The trend of those respondents who would like change is towards drier environments. Despite the question clearly asked about the perception of relative humidity relative regarding the indoor environment, some of the respondents answer about mould. About 50% of the respondents feel comfortable with the air movement conditions at the moment of the survey. Respondents in the warmer zones, low zone and mid zone, would prefer increased air movement inside the dwellings, 39% and 41% respectively. Whereas, a noticeable tendency towards less air movement (32%) is voted by participants in the high zone. Considering that the mean air movement for all zones is 0.3 m/s (±0.1 m/s), only participants in the high zone would prefer lower air movement. This finding denotes, to a certain degree, that human at hypobaric conditions are more sensitive to draught as results in previous studies (Wang et al., 2010). Lastly, the overall satisfaction with the indoor environment of participants follows the same trend as temperature votes. The higher rates of satisfaction were found in the lower zone (79%) followed by the mid zone (71%) and finally the high zone with the lower rate of satisfaction (63%).

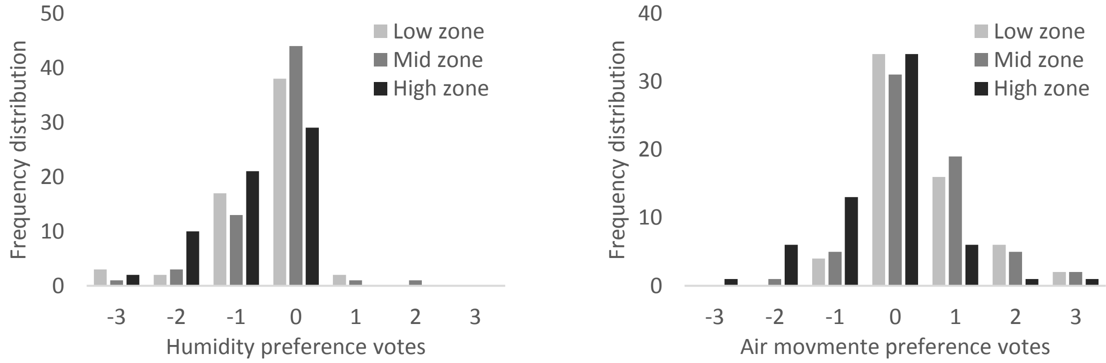


Figure 9: Distribution of humidity and air movement preference votes

A high percentage of respondents have mentioned in the survey that they feel colder when it is raining. In order to analyse if this cooler sensation is only related with lower temperature three consecutive rainy days (4 October – 6 October) and three consecutive days with high solar radiation (18 October – 20 October) are plotted in Figure 10. During the rainy days, the mean outdoor air temperature is 15.6°C (±2.9) in the low zone, 13.8°C (±2.6) in the mid zone, and 11.0°C (±2.3), almost equal to the mean daily temperature (Table 3). Opposite to the mean relative humidity that raises 9%, 11% and 16% from the mean daily relative humidity (Table 3). On the other hand, thru the days of high solar radiation the mean outdoor air temperature is one degree higher than the mean outdoor air temperature and relative humidity drops below at least 30% from the mean values reported in Table 3.

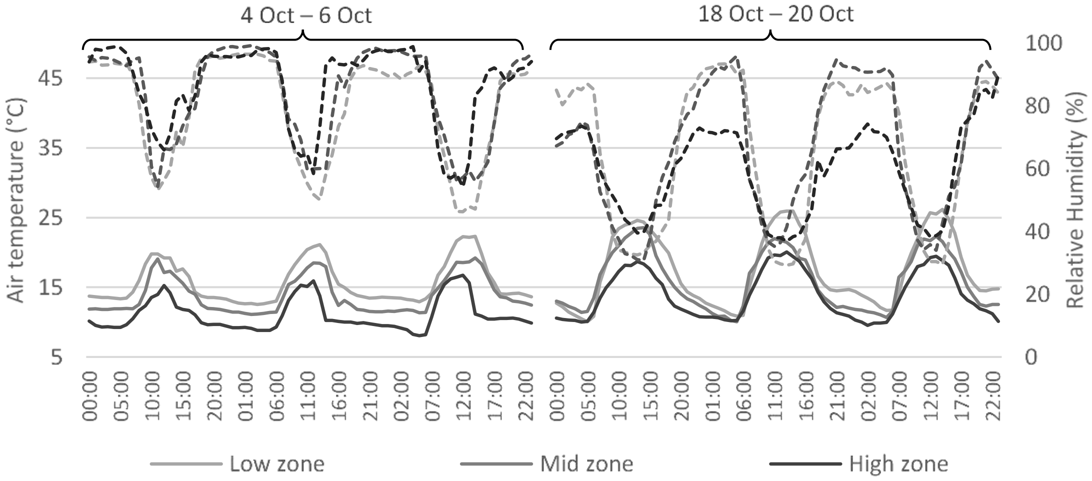


Figure 10: Outdoor air temperature and relative humidity for rainy and sunny days

To conclude this section, each thermal sensation vote was plotted against the corresponding globe temperature in Figure 11. The votes plotted in the graphic are dispersed denoting the flexibility of occupants to adjust their clothing, their activity, their posture and when possible the temperature and air movement (Nicol, 2004). In the high zone, operative temperatures between 16°C to 26°C are considered comfortable. A similar trend is observed for the other two zones where the comfortable operative temperature ranges are 18°C to 28°C in the mid zone and 20°C to 27°C in the low zone.

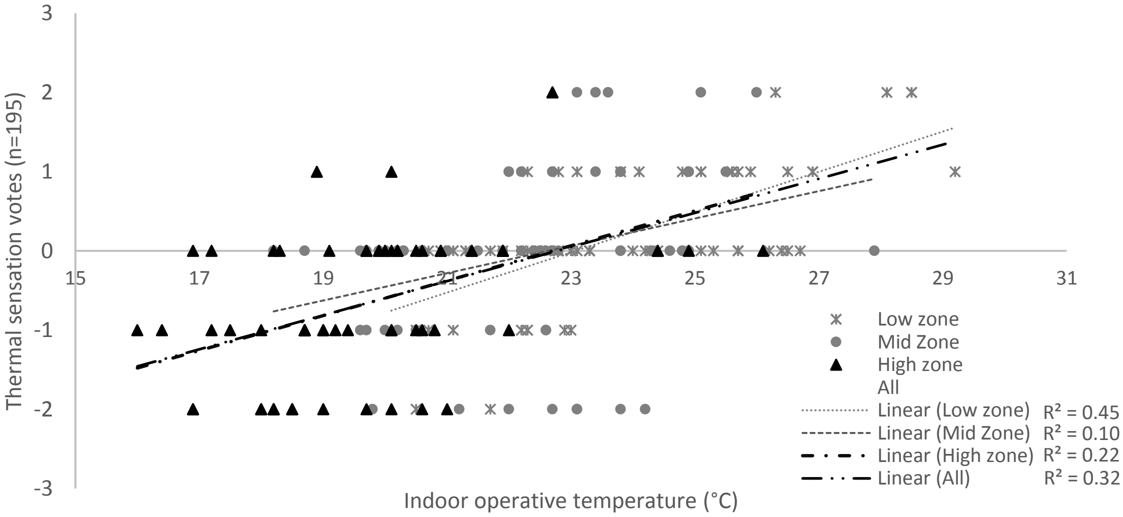


Figure 11: Scatter plot of thermal sensation votes and indoor operative temperature

7. The comfort zone and derivation of comfort temperature

The comfort zone is usually considered as the “three central categories” on the thermal sensation scale (Rijal, Yoshida and Umemiya, 2010). For this study the “thermal comfort zone” was defined from -1 to +1 (Slightly cool, neither warm nor cool, slightly warm) from a seven-point thermal sensation scale. The corresponding mean operative temperature for the thermal comfort zone is 23.4°C (SD±1.8) in the low zone, 22.4°C (SD±2.0) in the mid zone and 20.1°C (SD±2.1) in the higher zone. A high standard deviation of operative temperature (>1.0) can be attributable to people adaptive response (Humphreys, Nicol and Roaf, 2016), to poor construction of buildings and differences between dwellings materials.

Neutral or comfort temperature is often calculated by regression models that consider blocks of data from thermal comfort surveys (Rijal, Yoshida and Umemiya, 2010). A block of data usually contains the results of a day’s survey in a particular building or deliberately selected subsets in the database (Humphreys, Rijal and Nicol, 2013). The data for this study were collected from different individuals, at different daytime, in 138 different dwellings. In other words, very few interviews were gather the same day in the same building, so statistics calculated from these blocks of data are of low precision (Humphreys, Rijal and Nicol, 2013). Thus, simple regression of small data sets is insufficient to produce a reliable regression to estimate the comfort temperature (Humphreys, Rijal and Nicol, 2013). The neutral temperature for a small sample, as in this study, can be estimated using an appropriate regression coefficient derived from the pooled surveys, this procedure is called the ‘Griffiths method’ (Humphreys, Nicol and Roaf, 2016). The neutral temperature (Tn) was derived for each individual ‘comfort vote’ through the following formula:

$$T_n = T_{op} - \mathrm{Ts}/b$$

Where T_{op} is the mean operative temperature, Ts is the thermal vote of each interview and b is the Griffiths regression coefficient ($b = 0.5$). The weighted linear regression of indoor operative temperature on neutral temperature is presented on Figure 12.

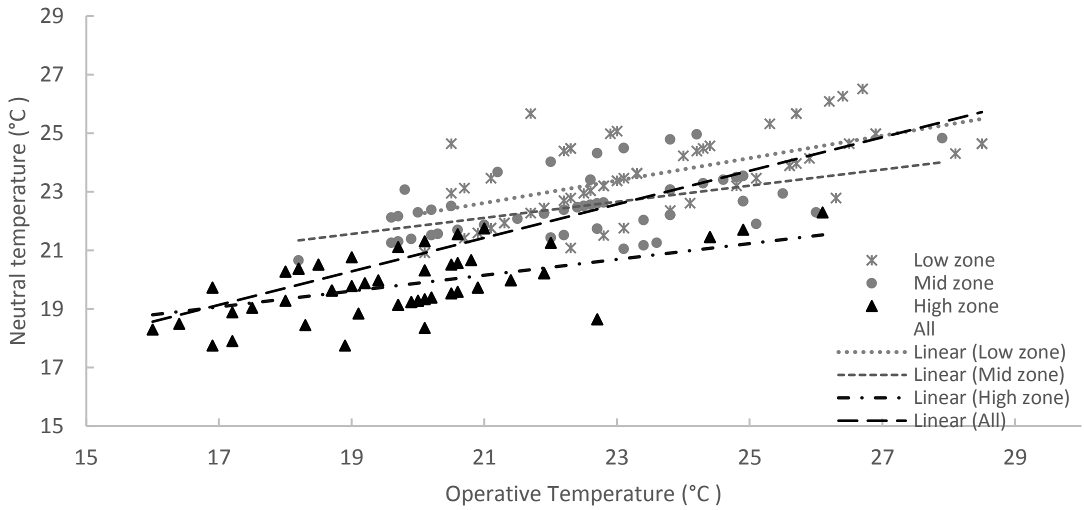


Figure 12: Relation between the operative temperature and neutral temperature

When calculating the neutral temperature from line-by-line data the obtained value is of very low precision but is free form systematic bias (Humphreys, Nicol and Roaf, 2016). The mean neutral temperature derived for each zone and the corresponding regression analysis are shown in Table 7. A decreasing mean neutral temperature is observed as altitude above sea level increase, similarly to the results of previous studies (Rijal, Yoshida and Umemiya, 2010). The derived results for the low zone (23.6°C) and mid zone (22.5°C) are likely the neutral temperature (21.1°C) derived for a location at 2600m, at Solukhumbu - Nepal (Table 1). The neutral temperature derived for the high zone is significantly below the one resulting for zones at higher altitudes, like in Lhasa where the neutral temperature for summer is 23.3°C (Yang et al., 2013).

Table 7: Neutral operative temperature regression analysis

	Mean T_n (°C)	SD	Linear regression equation	R^2
Low zone	23.6	1.3	$Tn = 0.38T_{op} + 14.6$	0.38
Mid zone	22.5	1.0	$Tn = 0.27T_{op} + 16.3$	0.28
High zone	19.8	1.0	$Tn = 0.27T_{op} + 14.5$	0.30
All zones	22.0	1.9	$Tn = 0.57T_{op} + 9.4$	0.58

8. Thermal adaptation

8.1. Physiological adaptation (acclimatisation)

At lower air pressure environments, the increment of the evaporative heat transfer is higher than the decrement of convective heat transfer (Ohno et al., 1991; Wang et al., 2010). As mention in (Yan et al., 2014), at hypobaric conditions the body heat loss is higher. Thus, an explanation of the trend towards warmer environment preference in high-altitude zones.

8.2. Behavioural adaptation

In terms of personal adjustments, the main actions described by participant as control actions to keep themselves warmer are shown in Figure 13. The main strategies used to be warmer are increasing clothing levels (67%), drinking hot beverages (27%), usage of blankets (14%) and going to bed (10%). Only 3% of the respondent's mention the usage of electric heater.

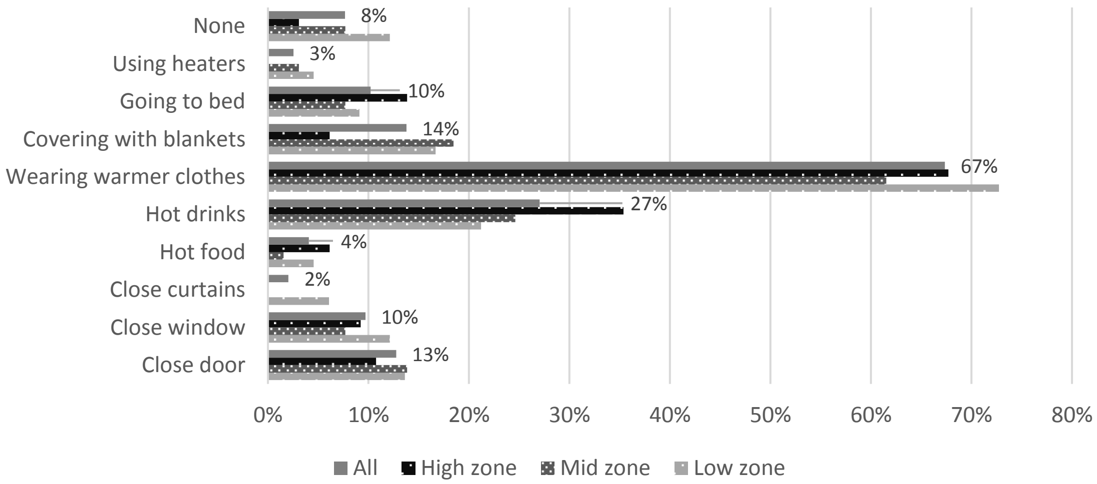


Figure 13: Methods of thermal adjustment to keep themselves warmer

In contrast, behavioural opportunities reported by respondents to keep cooler are wearing lighter clothing (50%), cold drinks (18%), changing rooms or going outside the building (8%), Figure 14. Curiously, 13% of the respondent reported taking a shower as an action to keep themselves cooler and 8% report to change room or going outdoors. Clothing insulation depends on participants preference as clothing patters are not regulated by climate or strong social custom or regulation. Regarding the windows and door operation, even though windows and doors are opened daily, this action is used indistinctly of being warm or not. Most of the people apply this control in warm days, however, it is more a habit for ventilating spaces or socialising activities such as keeping contact with neighbours.

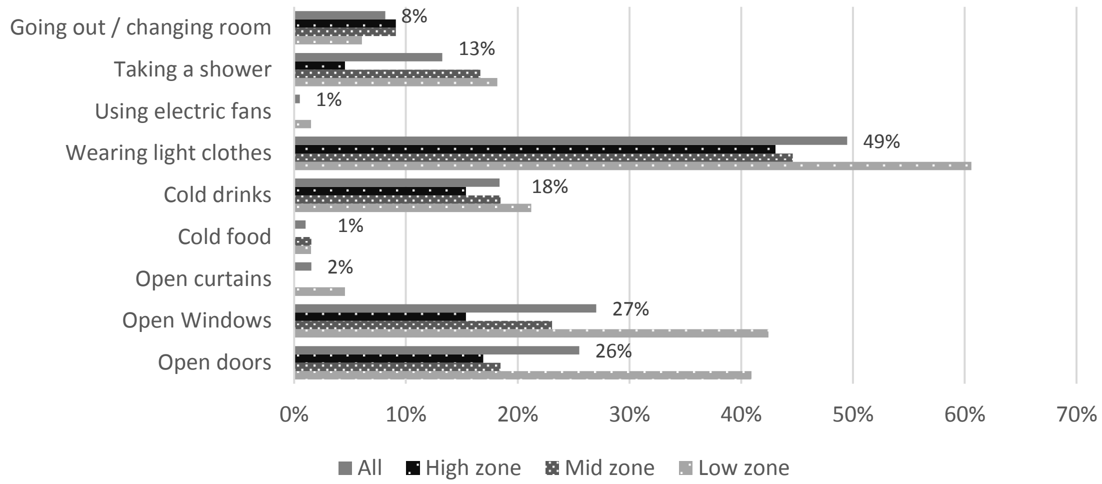


Figure 14: Methods of thermal adjustment to be cooler

8.3. Psychological adaptation

Several subjects reported that they are used to the indoor environment. The indoor environment expectations are very low as 92% of participants have not been exposed to air-conditioned buildings. Thus, they considered that there is nothing that can be done to improve the indoor environment. These occupants, who have been living in unconditioned and uninsulated building maybe even through generations, are more likely to be less severe when judging the indoor environment (Ole Fanger and Toftum, 2002).

9. Conclusions

Thermal comfort surveys were conducted in three altitude ranges in the Ecuadorian Andes in Quito. The low zone was defined between 2300 – 2400 meters above sea level, the mid zone between 2600 – 2700 m and a high zone between 3000 – 3100 m. The main conclusions of this work are:

- Clothing insulation varied from 0.33 clo in the low zone to 1.23 clo in the high zone. The wide variation range indicates certain degree of behavioural adaptation in response to the variation in the indoor air temperature. This assumption is supported with the high rate of respondents that report changing in clothing insulation as the first action to keep cooler (49%) or warmer (67%).
- In the low zone (2300 m – 2400 m), 90% of participants thermal sensation vote towards feeling comfortable at their indoor environment. As a response to the high indoor temperature (max 28.5°C), 39% of the participant vote for preferring higher air movement. The mean operative temperature for neutral votes is 23.4°C (SD±1.8) and the derived neutral temperature is23.6°C (SD±1.33). Lastly, overall satisfaction with the indoor environment reach a 79%.
- The mid zone votes are more consistent amongst the different indoor environment parameters. Around 70% of participants feel comfortable with the indoor globe temperature at the moment of the survey. The higher percentage of preference for an increased air movement (41%) correspond to the mid zone. The mean operative temperature for neutral votes is 22.4°C (SD±2.0) while the derived neutral temperature is 22.5°C (SD±1.03).
- The highest rate of thermal sensation votes towards feeling slightly cool (29%) and cold (23%) are observed in the high zone. 61% of the participant would prefer warmer

environments, in addition, 53% of respondents would prefer drier environments. Moreover, participants tend to be more sensitive to draught, 32% of the them reported to prefer reduced air movement. Lastly, the mean operative temperature for neutral votes is 20.1°C (SD±2.1) and the derived 19.8°C (SD±1.01).

Future work will include the collection of thermal comfort data in the subtropical highlands in the rainy period, as well as, a robust analysis of the adaptation strategies of users in the Ecuadorian Andes and the influence of other environmental parameters.

Notwithstanding the small data set, the results of this study are useful to understand the level of satisfaction of resident in the highland in the Ecuadorian Andes to the indoor environment in dwellings. Further research is required so that larger data sets are available to predict reliable thermal comfort models for the subtropical highlands.

Acknowledgements

The authors would like to acknowledge the financial support provided by the National Secretary of Higher Education, Science, Technology and Innovation (SENESCTY). Furthermore, the research team is thankful for assistance provided by Mr Alex Toasa and Ms Adriana Cuenca as well as the families that participated in the surveys.

References

Amante, C. and Eakins, B. W. (2009) *ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24*. National Geophysical Data Center, NOAA. doi: 10.7289/V5C8276M.

ASHRAE (2009) *2009 Ashrae Handbook Fundamentals*.

ASHRAE (2010) 'STANDARD 55 - 2010 Thermal Environmental Conditions for Human Occupancy', *Ashrae Standard*. Atlanta, GA, US, p. 30. doi: ISSN 1041-2336.

Castilla, M. M. *et al.* (2010) 'Técnicas de Control del Confort en Edificios', *Revista iberoamericana de automática e informática industrial*, 7(3), pp. 5–24. doi: 10.4995/RIAI.2010.03.01.

CONELEC and CIE (2008) *Atlas Solar del Ecuado con fines de Generación Energética*. Quito.

Dear, R. De *et al.* (1998) 'Developing an adaptive model of thermal comfort and preference', *ASHRAE Transactions*, 104(Part 1), pp. 1–18. Available at: https://escholarship.org/uc/item/4qq2p9c6.pdf%5Cnhttp://escholarship.org/uc/item/4qq2p9c6.pdf%5Cnhttp://repositories.cdlib.org/cedr/cbe/ieq/deDear1998_ThermComPref (Accessed: 26 November 2016).

Emck, P. (2007) *A Climatology of South Ecuador*. Universität Erlangen-Nürnberg.

Forgiarini Rupp, R., Vásquez Giraldo, N. and Lamberts, R. (2015) 'A review of human thermal comfort in the built environment', *Energy and Buildings*. Elsevier B.V., 105, pp. 178–205. doi: 10.1016/j.enbuild.2015.07.047.

Fuller, R. J., Zahnd, A. and Thakuri, S. (2009) 'Improving comfort levels in a traditional high altitude Nepali house', *Building and Environment*, 44(3), pp. 479–489. doi: 10.1016/j.buildenv.2008.04.010.

Gomez, C., Morales, G. and Torres, P. (2011) 'Sensación térmica percibida en vivienda económica y auto-producida, en periodo cálido, para clima cálido húmedo', *Ambiente Construído, Porto …*, 11, pp. 99–111. doi: 10.1590/S1678-86212011000400008.

Hidalgo, M. a G. and Zavala, D. V. (2007) *Estándar local de Confort Térmico para la ciudad de Colima*. Universidad de Colima. Available at: http://digeset.ucol.mx/tesis_posgrado/Pdf/RUIZ_TORRES_RAUL_PAVEL.pdf (Accessed: 24 May 2017).

Huang, L. *et al.* (2016) 'Climate-responsive design of traditional dwellings in the cold-arid regions of Tibet and a field investigation of indoor environments in winter', *Energy and Buildings*, 128, pp. 697–712. doi: 10.1016/j.enbuild.2016.07.006.

Humphreys, M. A., Nicol, J. F. and Roaf, S. (2016) *Adaptive Thermal Comfort Foundations and Analysis*. 1st Editio. Routledge Taylor & Francis Group.

Humphreys, M. A., Rijal, H. B. and Nicol, J. F. (2013) 'Updating the adaptive relation between climate and comfort indoors; new insights and an extended database', *Building and Environment*. Elsevier Ltd, pp. 40–55. doi: 10.1016/j.buildenv.2013.01.024.

ISO (2004) ‘BS EN ISO 8996:2004 Ergonomics of the thermal environment Determination of metabolic rate’, 3, pp. 1–14. doi: 10.3403/03205220.
ISO (2005) ‘BS EN ISO 7730:2005 Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria’, *Management*. London, United Kigdom: British Standards Institution (BSI), p. 64. doi: 10.1016/j.soildyn.2004.11.005.
ISO (2007) ‘BS EN 15251:2007: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics’. London, UK: British Standards Institute (BSI), p. 56. doi: 10.1520/E2019-03R13.Copyright.
Llaneza, F. J. (2008) *Ergonomía y psicosociología aplicada : manual para la formación del especialista*. Lex Nova. Available at: https://books.google.co.uk/books?id=KOoQjcw2ZZUC&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false (Accessed: 24 May 2017).
Nicol, F. (2004) ‘Adaptive thermal comfort standards in the hot-humid tropics’, in *Energy and Buildings*, pp. 628–637. doi: 10.1016/j.enbuild.2004.01.016.
Nicol, F. and Humphreys, M. (2010) ‘Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251’, *Building and Environment*. Elsevier Ltd, 45(1), pp. 11–17. doi: 10.1016/j.buildenv.2008.12.013.
NREL (2016) ‘Weather Data for Simulation’, *EnergyPlus*. Available at: https://energyplus.net/weather/simulation.
Ohno, H. *et al.* (1991) ‘The effects of hypobaric conditions on man’s thermal responses’, *Energy and Buildings*, 16(1), pp. 755–763. doi: 10.1016/0378-7788(91)90048-8.
Ole Fanger, P. and Toftum, J. (2002) ‘Extension of the PMV model to non-air-conditioned buildings in warm climates’, *Energy and Buildings*, 34(6), pp. 533–536. doi: 10.1016/S0378-7788(02)00003-8.
Peel, M. C., Finlayson, B. L. and McMahon, T. A. (2007) ‘Updated World Map of the Koppen-Geiger Climate Classification Updated world map of the K ¨ oppen-Geiger climate classification’, *Hydrology and Earth System Sciences*, (October 2007). doi: 10.5194/hess-11-1633-2007.
Rijal, B. H. and Yoshida, H. (2006) ‘Winter Thermal Comfort of Residents in the Himalaya Region of Nepal’, in *Proceeding of international conference on comfort and energy use in buildings—getting them right (Windsor)*.
Rijal, H. B. B., Yoshida, H. and Umemiya, N. (2010) ‘Seasonal and regional differences in neutral temperatures in Nepalese traditional vernacular houses’, *Building and Environment*. Pergamon, 45(12), pp. 2743–2753. doi: 10.1016/j.buildenv.2010.06.002.
Secretaria del ambiente Quito (2004) *Datos REMMAQ*. Available at: http://www.quitoambiente.gob.ec/ambiente/index.php/indice-de-calidad-del-aire-2 (Accessed: 2 January 2018).
Vebraecken, J. *et al.* (2006) ‘Body surface area in normal-weight, overweight, and obese adults. A comparison study’, *Metabolism: Clinical and Experimental*, 55(4), pp. 515–524. doi: 10.1016/j.metabol.2005.11.004.
Wang, H. *et al.* (2010) ‘Experimental study of human thermal sensation under hypobaric conditions in winter clothes’, *Energy and Buildings*, 42(11), pp. 2044–2048. doi: 10.1016/j.enbuild.2010.06.013.
Yan, H. *et al.* (2014) ‘Indoor thermal conditions and thermal comfort in residential buildings during the winter in Lhasa, China’, in *Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a changing world*, pp. 68–86. Available at: http://nceub.org.uk (Accessed: 27 November 2016).
Yang, L. *et al.* (2013) ‘Residential thermal environment in cold climates at high altitudes and building energy use implications’, *Energy and Buildings*. Elsevier B.V., 62, pp. 139–145. doi: 10.1016/j.enbuild.2013.02.058.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

The courtyard pattern's thermal efficiency: Limits and significance of impact

Omar Al-Hafith[1], Satish B K[1], Simon Bradbury[2] and Pieter de Wilde[1]

[1] Plymouth University, ADA School, Plymouth, UK.;
[2] De Montfort University, Leicester, UK

Abstract: The courtyard pattern has been advocated as a thermally efficient design for hot regions. Many studies have been yielded the suggestion of re-introducing this building pattern for its thermal efficiency. However, it has not been widely investigated to which extent courtyards actually provide thermal comfort for people. By examining the thermal behaviour of 360 courtyards, this paper investigates the impact of courtyards' geometry and orientation on its thermal conditions and occupants' thermal sensation. Baghdad was used as a case study due to its hot climate and traditional use of courtyards. A comfortable temperature for hot climate defined by a previous study was used to judge the tested courtyards. Calibrated Envi-met simulation models have been used to determine courtyards' thermal conditions. The results show that the most effective design parameter on courtyards' thermal efficiency is the courtyard's Width/Height and the most effective climatic factor is the Mean Radiant Temperature. The thermal efficiency increases by having deep and small courtyards. If properly designed, courtyards can provide 4-7 ^{o}C less Globe Temperature than the outdoor temperature, while improperly designed ones can be 20^{o}C higher than the outdoor temperature. In all cases, courtyard spaces cannot provide thermal comfort if the outdoor Globe Temperature exceeded 38^{o}C.

Keywords: Courtyard pattern, thermal efficiency, thermal comfort, Baghdad,

1. Introduction

For the last three decades, the courtyard pattern has been widely investigated and analysed to determine its thermal efficiency. It has been concluded that, when properly designed, the courtyard pattern is more thermally efficient than other building patterns in hot climate regions (Edwards, 2006); (Al-Azzawi, 1984); (Al Jawadi, 2011). However, it is still not clear to which extent it is a thermally comfortable space for the people who are adapted to air-conditioned spaces, which is an essential aspect in assessing the courtyard's thermal efficiency (Ghani et al., 2016). This research focuses on this question. To achieve this, first, courtyard pattern's thermal efficiency, thermal comfort and previous relevant literature were explored. Then, a simulation experiment using Envi-met 4.2 was conducted to determine the thermal conditions for various courtyard configurations.

1.1. The courtyard pattern

By definition, the courtyard pattern consists of a building with an open space in its core, which provides access and natural lighting and ventilation to surrounding indoor spaces (Al-Hafith et al., 2017c); (Soflaei et al., 2017). This building pattern has been used in hot regions for a long period until the introduction of modern architectural styles and construction technologies at the beginning of the 20th century (Al-Hafith et al., 2017b); (Sthapak and Bandyopadhyay, 2014). Since that time, modern building patterns, such as detached and semi-detached buildings, have been used, which rely on mechanical air-conditioning to provide thermal comfort. This has led to an increase in running costs, energy consumption and CO_2 emissions (Foruzanmehr, 2015). In the general quest for environmental solutions, the courtyard pattern's thermal efficiency has been tested and proven experimentally by many researchers, such as Cho & Mohammadzadeh (2013) in Iran, Al-Masri (2012) in the UAE, Al Jawadi (2011) in Iraq, Manioğlu & Yılmaz (2008) in Turkey and Edwards (2006) in Saudi Arabia. They have shown that the courtyard pattern yields more thermally efficient and less energy consuming buildings than modern non-courtyard patterns.

The thermal efficiency of a courtyard building depends on two main strategies: controlling the buildings' exposure to solar radiation and providing sufficient natural ventilation (Ali and Shaheen, 2013a); (Agha, 2015); (Al-Hemiddi and Megren Al-Saud, 2001). In the courtyard space, shading protects from having heat gain resulted from solar radiation (Shaheen and Ahmad, 2011a); (Al Jawadi, 2011). Natural ventilation, brought about by buoyancy created by warm air rising in reaction to release of accumulated heat in the courtyard's surrounding surfaces, helps to get rid of the heat from the courtyard, and will cause the surrounding indoor spaces' hot air to be replaced by cooler air (Moosavi et al., 2014) ;(Mohammed, 2010). This thermal behaviour is mostly dependent on the courtyard geometric properties, these are width, length, height and orientation (Muhaisen and Gadi, 2006); (Al-Hafith et al., 2017a). If the courtyard space is improperly designed and has inefficient shading and natural ventilation, the performance of the courtyard building may become less efficient than other possible building patterns (El-deep et al., 2012); (Aldawoud and Clark, 2008); (Ratti et al., 2003).

1.2. Thermal comfort

Thermal comfort is one of the factors that affect people's overall comfort in built environments (Al horr et al., 2016); (Frontczak and Wargocki, 2011). It has also relations with health (ASHRAE, 2005), productivity (Elaiab, 2014), energy consumption (Nicol et al., 2012), CO_2 emissions (Elaiab, 2014), and the use of indoor and outdoor spaces (Chen and Ng, 2012). Thermal comfort has been defined by ASHRAE as 'that condition of mind that expresses satisfaction with thermal environments' (ASHRAE, 2005); (Enescu, 2017); (Höppe, 2002). Scholars have shown that this subjective feeling is related to the surrounding environments' features and the human body thermal balance (Enescu, 2017); (Elaiab, 2014); (Höppe, 2002).

Within the framework of this definition, aiming at investigating and determining people's thermal sensation and comfort temperature, scholars have explored the key comfort factors that determine thermal comfort (Nicol and Roaf, 2017); (Passe and Battaglia, 2015). It is well known now that these factors can be classified into two groups: quantitative factors and qualitative factors. The former includes air temperature, air velocity, humidity, Mean Radiant Temperature (MRT), clothing and activity levels (Reiter and De Herde, 2003); (Nikolopoulou, 2011). The other category includes various factors such as people's thermal expectation and past experience, time of exposure to specific conditions, people's potential control over climatic conditions, and people's psychological factors (Aljawabra, 2014); (Nikolopoulou, 2011); (Höppe, 2002).

Aiming for a single measure that combines the effective factors to indicate people's thermal sensation and predict thermal comfort limit, various studies have been done since 1905 and more than 100 indices have been developed (Epstein and Moran, 2006); (Fabbri, 2015). These indices have been introduced and used within the framework of two thermal comfort models: the Static model and Adaptive model (Nikolopoulou, 2011); (de Dear and Brager, 2002). The first model depends fundamentally on the thermal balance between the human body and its surrounding environment, proposing a steady and universal thermal comfort limit (Reiter and De Herde, 2003); (Nikolopoulou et al., 2001). Among the widely used indices of this model are the Predicted Mean Vote (PMV), the Standard Effective Temperature (SET), the Physiological Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI) (Nikolopoulou, 2011). The second model, argues that thermal sensation is dynamic and cannot be found from the human body balance factors only (Nicol et al., 2012); (de Dear and Brager, 2002). It assumes that people can adapt themselves to their surrounding contextual climate and that people from different places and regions are different in their thermal sensations. (de Dear and Brager, 2002); (de Dear and Brager, 1998); (Nicol, 2004); (Nicol and Humphreys, 2002). Thermal comfort limit is defined in this model by conducting thermal comfort surveys (Nicol et al., 2012); (de Dear and Brager, 2002), and using direct thermal comfort indices that combine a number of climatic factors in one value expressing the temperature felt by people. Among the widely used adaptive indices are Dry and Wet Bulb Temperatures, Globe Temperature (Tg), Wet Bulb Globe Temperature (WBGT) and Operative Temperature (To) (Song, 2011).

Many of these indices and both of the Static and the Adaptive models are used to define the limits in international thermal comfort standards such as EN 15251 , ASHRAE and ISO Standard 55 (Nicol et al., 2012); (Rupp et al., 2015). However, studies have shown that the Adaptive model's prediction is closer to the actual people thermal sensation than the Static model, especially in naturally ventilated spaces. The Static model overestimates people thermal discomfort (Kim et al., 2015); (Nicol et al., 2012), and is not applicable in outdoor and semi-outdoor spaces (Rupp et al., 2015). The main reason behind this is that the Static model does not consider the social and contextual factors, people's adaptation abilities and the dynamicity of environments' thermal conditions (Nicol et al., 2012); (Nikolopoulou et al., 2001). Accordingly, to determine the courtyard space's thermal efficiency, the Adaptive model's indices should be used.

1.3. Thermally comfortable courtyard spaces - literature review

The thermal behaviour of courtyard buildings has been the subject of many studies since the 1980s. The aim of most of this work has been to describe, investigate, analyse and determine courtyard buildings' efficiency in providing thermal comfort. Studies have used different approaches, such as real life measurements, surveys and simulation. This has led to a growing awareness about courtyards' thermal behaviour and the various effective factors (Al-Azzawi, 1984); (Meir et al., 1995); (Nasrollahi et al., 2017). This paper classifies the conducted studies in this field according to their defined aims into three categories:

1. Describing courtyard thermal behaviour: this group includes the earlier studies in this field. Their focus has been to explore and describe the courtyard pattern's thermal behaviour. Literature review or real life measurements have been their main research methods. As an example, an early PhD study was conducted at University College London (UCL) in 1984. It included comparing the thermal conditions of three courtyard houses and three non-courtyard houses in Baghdad during two weeks in summer and winter. The study concluded that, in Baghdad's long and hot summer, courtyard houses provide a more thermally comfortable environment than the modern non-courtyard houses (Al-Azzawi, 1984). Other studies in this group with similar results include El-Harrouni (2015) in Morroco, Al-Jawadi (2011) in Iraq, Sadafi et al. (2011) in Malaysia, Manioglu & Yılmaz (2008) in Turkey and Al-Hemiddi & Megren (2001) in Saudi Arabia.
2. Analysing the courtyard thermal behaviour: this group follows and builds on the previous group of studies. Here, more in-depth attention has been paid to the thermal behaviour of the courtyard pattern. The main aim has been to determine the impact of

courtyard's geometry, orientation, construction materials, contextual climate and openings on its shading and natural ventilation and the resulted thermal conditions (Aldawoud and Clark, 2008); (Soflaei et al., 2017); (Nasrollahi et al., 2017). Studies by Muhaisen (2006) and Muhaisen and Gadi (2006, 2005) widely explored and analysed courtyard shading in different contexts. Their main results included that courtyards get better shading by increasing their height, decreasing their Width/Length ratio and having a specific orientation for each geographical location in correspondence with the sun's angles. These results are supported by other studies, such as Al-Hafith et al. (2017) in Iraq and Soflaei et al. (2017) in Iran. Regarding natural ventilation, it has been found that wide courtyards have more active natural ventilation than narrow ones (Bittencourt and Peixoto, 2001). It has also been found that natural ventilation is affected by courtyard's openings size and location (Rajapaksha et al., 2002); (Soflaei et al., 2016); (Mousli and Semprini, 2016). Having cross ventilation enables higher air flow than if there are opening from all sides (Soflaei et al., 2016).

3. Analysing thermal comfort in courtyard spaces: developments in the available research methods, such as building performance simulation and modern meteorological instruments, have enabled researchers to further advance in this field: relating courtyards' performance to occupants' thermal sensation. Amongst the researchers who have investigated this aspect are Soflaei et al. (2017) in Iran, Martinelli & Matzarakis (2017) in Italy, Nasrollahi et al. (2017) in Iran, Mousli & Semprini (2016) in Syria, Ghaffarianhoseini et al. (2015) in Malaysia, Almhafdy et al. (2015) in Malaysia and Berkovic et al. (2012) in Israel. They have used either simulation tools with thermal comfort indices or real life measurements with thermal comfort surveys to assess courtyard occupants' thermal sensation. In the first case, they have mostly used the Envi-met simulation tool with static thermal comfort indices to assess a range of courtyard configurations. In the second case, they have assessed thermal sensation in a limited number of cases with specific configurations.

According to the literature review presented in this paper, it can be concluded that courtyards can, through passive systems, provide a higher level of thermal comfort for its occupants compared to other building patterns. Shading and natural ventilation have a significant impact on courtyards' thermal behaviour. Using an appropriate courtyard design is essential to get the courtyards' thermal efficiency (Ghaffarianhoseini et al., 2015); (Aldawoud and Clark, 2008, Soflaei et al., 2017);(Nasrollahi et al., 2017). However, there are still knowledge gaps that need to be filled:

1. While the impact of courtyard configurations on shading has been intensively investigated, there has been limited work to investigate the impact of courtyard configurations on its thermal comfort related climatic conditions: air temperature, air velocity, MRT and humidity.
2. There has been no attempt to determine the impact of courtyard configuration on an adaptive thermal comfort index to predict people's thermal perception.

2. Research's aim and methodology

This research aims to analyze the impact of the courtyard space's parameters on its thermal conditions and achieving thermal comfort in hot regions. More specifically, it determines the impact of courtyard's orientation and geometrical parameters on its climatic conditions affecting occupants' thermal comfort.

To achieve this aim, this research used Envi-met 4.2, an outdoor environmental simulation tool, to determine the thermal conditions of 360 courtyard configurations during summer in Baghdad. This city was used as a case study for its extremely hot and long summer and its long history of using the courtyard pattern. Regarding the Envi-met 4.2 simulation tool suitability and validity, further details are provided in Section 2.3.

2.1. Research variables

This research has three kinds of variables: Independent variables, mediating variables and a dependent variable (Fig.1). The former represents the causes, the last one represents the results and the mediating variables represent intervening factors. The impact of the independent variables can be seen on mediating variables before reaching dependent variables. Exploring the subject in this way helps to develop a comprehensive idea of a phenomenon (Creswell, 2014).

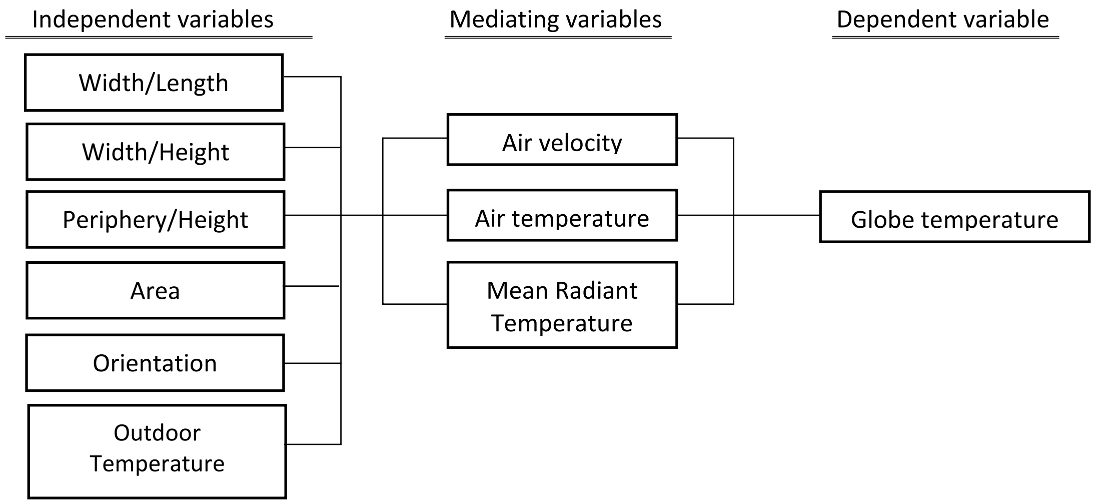


Figure 1. The research variables and their relations

In the research presented in this paper, the dependent variable is occupants' thermal sensation. As the courtyard is a semi-outdoor space (Rupp et al., 2015), the Globe Temperature, an adaptive thermal comfort index, was selected to quantify thermal sensation in the tested configurations. Globe Temperature has been widely used in thermal comfort studies as it has been found that it shows acceptable correlation with the people actual thermal sensation (Toe and Kubota, 2011). As a measurement, it combines the effects of air velocity, air temperature and MRT (Song, 2011). To assess the courtyard ability to provide thermal comfort, a thermal comfort upper limit was defined using the results of a thermal comfort survey conducted by Aljawabra in Marrakech (Aljawabra, 2014). Exploring previous studies showed that the case study in Marrakech, is the closest available study to Baghdad's summer temperature and people culture. According to this study, the maximum Globe Temperature that people may accept in summer is 36°C.

The independent variables are the courtyard's ratios of Width/Length (W/L), Width/Height (W/H), Periphery/Height (P/H), the ground area and long axis orientation. These parameters have been defined as the effective variables on courtyard's thermal conditions (Muhaisen, 2006); (Al-Hafith et al., 2017a). The ground area has been rarely investigated in previous studies, but the research presented in this paper included it in its analysis for the impact of the distance between the subject and the courtyard's surfaces on MRT, which cannot be captured by the other variables (ASHRAE, 2005). Outdoor Globe temperature (Tgout) is the final independent variable, which is uncontrolled and not related to courtyard's configuration, but is essential to have a comprehensive analysis, as the courtyard is a semi-outdoor space. Globe temperature was selected to represent the outdoor condition because it includes three climatic factors and can be used to make comparisons with this research's thermal sensation index.

Mediating variables are the courtyard's climatic conditions that affect its Globe Temperature, this research thermal sensation index, which are air temperature (Ta), MRT and air velocity (Av) (Song, 2011). To have a comprehensive analysis of people's thermal precipitation in courtyards, this research determines the impact of the courtyard configurations on each of these variables. As it is stated in Section 2, Envi-met simulation tool was used to determine each of these three variables in each of the 360 tested courtyard configurations. Then, Globe Temperature was calculated using a special equation, as it is not measurable in Envi-met.

2.2. Tested courtyard configurations

In order to study a wide range of the possible courtyard configurations and their relation to thermal efficiency, 360 courtyard configurations were developed and tested. They include six different areas, five W/L ratios, three heights and four orientations, representing most of the possible courtyard configurations (Figure 2.). These 360 options help to give a comprehensive idea of the impact of each of the effective factors on the environmental conditions and thermal perception.

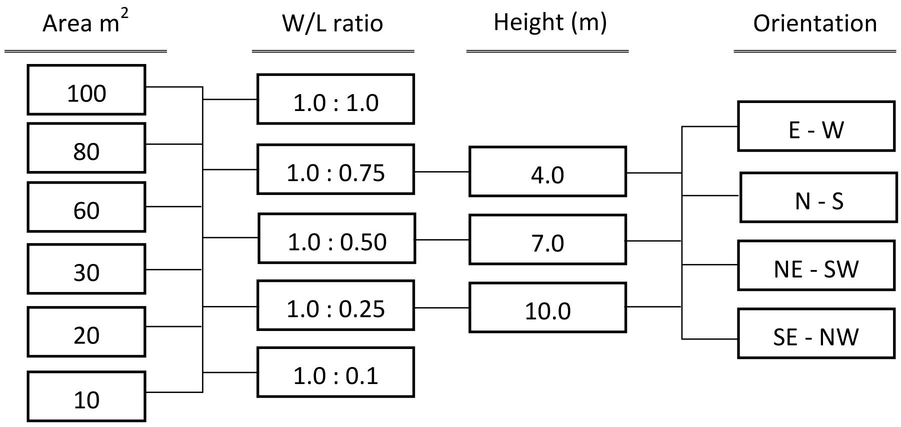


Figure 2. The tested courtyard configurations' variations

2.3. The simulation experiment

Envi-met 4.2, a CFD simulation tool, was used to determine the thermal conditions of the selected courtyard configurations. Envi-met simulates the interactions between building surfaces, air and natural elements on a micro scale of urban spaces, such as streets, plazas and courtyards (Berardi, 2016); (ENVI-MET, 2017). It depends on well-based physical and fluid dynamics rules and principles in considering the impact of wide-range effective factors on outdoor spaces' environments. Among the factors that it considers are long and short waves radiation, air temperature, wind velocity, humidity and vegetation (Hedquist and Brazel, 2014); (Malekzadeh, 2009), which are not offered by other similar simulation tools (Taleghani et al., 2015). The software versions before version 4.2 had a number of drawbacks, which included mainly the problem of determining buildings heat storage during the day-time and radiation during the night-time, which led sometimes to inaccurate results (Berkovic et al., 2012); (Hedquist and Brazel, 2014). However, this problem has been solved with the newly introduced improvements on the software during the previous two years (Simon, 2016). Many studies have validated its results by making comparisons between the software simulation results and real-life measurements (Nasrollahi et al., 2017); (Hedquist and Brazel, 2014); (Ridha, 2017).

In order to get true simulation results, the simulation model was calibrated before testing this research's courtyard configurations. For this purpose, simulation results were compared with real life measurements of two courtyard houses in Baghdad obtained from a third party measurement effort (Al-Azzawi, 1984); (Salman, 2016). The reference Baghdadi courtyard houses were modelled in Envi-met, then their courtyards' surfaces properties were fine-tuned until the simulation results became visually similar to the real life conditions (Figure 3). To check the validity of the calibration and the accuracy of the results, a typical equation used in literature for quantifying accuracy was used: Coefficient of Variation for the Root Mean Squared Error (CV-RMSE) (Eq1). This equation gives a percentage showing how close the simulation is to real life conditions. Lower resultant values indicate a better-calibrated model (Bagneid, 2010); (Haberl and Bou-Saada, 1998). According to ASHRAE standard, for hourly data simulation, the simulation model can be declared to be calibrated if the result of this equation is within ± 30% (Bagneid, 2010).

$$\text{CV-RMSE} = ((\sum (D_a - D_d)^2 / P - 1))^{0.5} / D_{aa} \quad \text{------ (Eq1)}$$

where :

D_p = the predicted data, D_a = the actual data, D_{aa} = the average value of the actual data, P = the number of data points

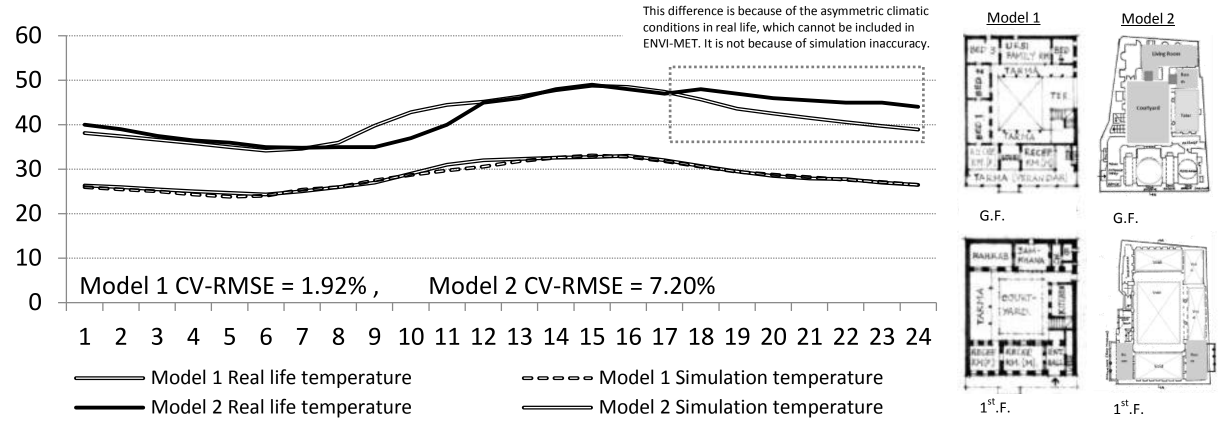


Figure 3. The comparison between courtyard houses' real and simulation temperature (left), and the plans of the used Baghdadi courtyard houses (right).

A simulation experiment was carried out for Baghdad's climate on the 12th of July, the hottest day, to determine the courtyard performance in the extreme scenario. Hourly climatic data of this day was obtained from unpublished data of the Iraqi meteorological organization for 2016. The conditions and parameters used in the software configuration file are shown in Table 1, which were based on this research's objectives and calibration, and settings used in previous similar studies (Nasrollahi et al., 2017); (Jiang, 2017).

Table 1. The values used in the software configuration file

Simulation parameters	Input value	Material parameters	Input value
Start date	**12/07/2017**	**Thickness**	**0.30 m**
Start time	**00:00:00**	**Absorption**	**0.80 Frac**
Total simulation time	**32 (hours)**	**Transmission**	**0.00 Frac**
Output interval for file	**30 (minutes)**	**Reflection**	**0.05 Frac**

Wind speed	**3.1 m/s**	**Emissivity**	**1.10 Frac**
Wind direction	**45**	**Specific heat**	**1300.0 J/(kg*k)**
Roughness length	**0.01**	**Thermal conductivity**	**0.30 W/(m*k)**
Max Tem. and time	**49.8 ^{o}C at 16:00**	**Density**	**1000.0 kg/m^{3}**
Min Tem. And time	**35.1 ^{o}C at 06:00**	**Note:**	
Max Hum. and time	**53 % at 06:00**	**• The first six hours of simulation results were not considered as the impact of stored heat in buildings on night thermal conditions is missed. • All of the not mentioned software's parameters were kept as default**	
Min Hum. and time	**24 % at 16:00**		
LBC (Lateral boundary condtions)	**Cyclic**		

3. The simulation results

The results include the air temperature, MRT and air velocity for each of the tested alternatives. The measurements were taken in the centre of the tested courtyards at 1.5m height, which was considered to represent the courtyards' conditions and the perceived thermal sensation by occupants. The Globe Temperature was determined depending on the obtained values using the Globe Temperature equation (Eq2). The result of this equation was used to determine the temperature experienced by occupants in each of the tested courtyards. Comparing the resulted values with the defined comfort threshold of 36 ^{o}C determines how close the courtyards are in providing thermal comfort.

$$Tg= (MRT + 2.35 \times Ta \times (Av)^{0.5})/ (1 + 2.35 \times (Av)^{0.5}) \quad \text{------} \quad (Eq2)$$

3.1. The courtyards' thermal conditions

Exploring the simulation results shows that all of the cases average daily Globe Temperature is greater than the comfort temperature. The lowest value is 41.7 ^{o}C and the highest is 50.3 ^{o}C (Figure 4). The graph in Figure 5 shows the hourly Globe Temperature in the five courtyards with the lowest average daily temperature and the highest average temperature. It can be seen that all courtyards are not thermally comfortable during the day-time and comfortable during a part of the night-time. However, the difference in Globe Temperature that results from changing the courtyards' parameters is around 20 ^{o}C. The courtyards with the lowest average Globe Temperature are the small and deep ones. The inverse can be said about the courtyard with the hottest average Globe Temperature. Regarding the orientation, the results show that (E-W) and (N-S) orientations offer higher chances to provide more thermally comfortable conditions than the other two orientations.

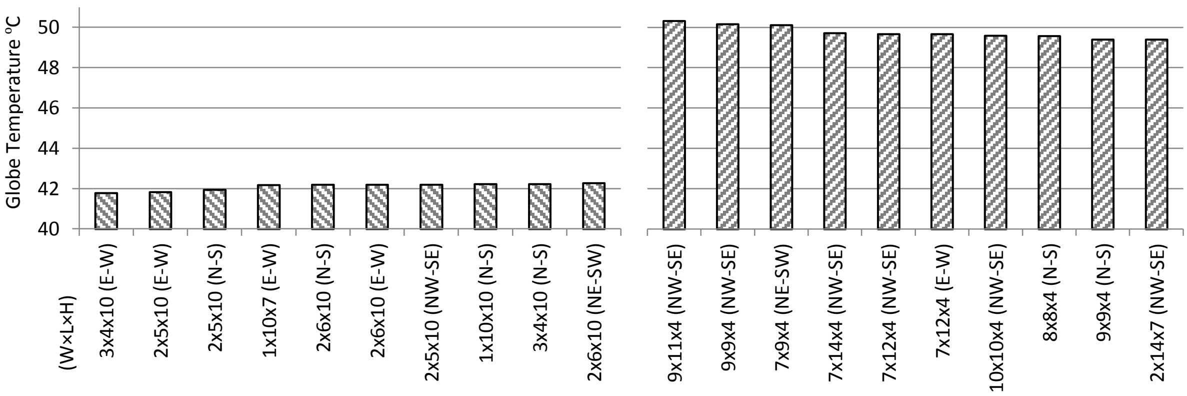


Figure 4. The ten lowest average daily Globe Temperature courtyards (left) and the ten highest average daily Globe temperature courtyards (right).

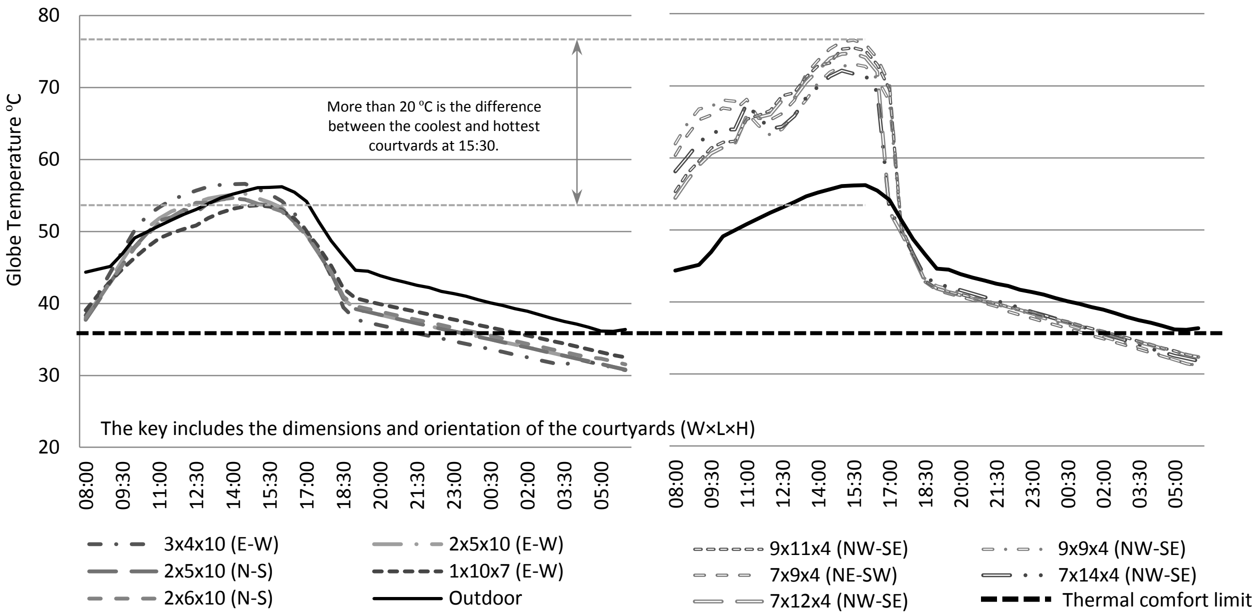


Figure 5. The hourly Globe Temperature in the five most thermally efficient courtyards (left) and the worst five courtyards (right)

3.2. Results analysis

To make useful recommendations and conclusions from the obtained results, it is essential to perform a statistical analysis, which includes regression and correlation analysis.

The results from the correlation analysis in (Table 2) show that there is a statistically significant correlation between all of the research variables ($P \leq 0.05$), except the correlations between courtyards' air velocity and thermal comfort. Regarding the significance of the impact of courtyards' parameters on its thermal conditions, the most effective parameter on its air temperature and MRT is the W/H ratio, while on air velocity; it is the P/H ratio. The most effective courtyard design parameter on thermal comfort is W/H ratio. The most effective climatic parameter on occupants' comfort is the MRT. It is essential also to state that the outdoor conditions, represented here by the Globe temperature, has the most significant impact on occupants' thermal sensation. It has around ten times higher impact than all of the courtyards' design parameters (Figure 6). Regarding the impact of courtyard orientation on its thermal conditions, it was not included in the statistical analysis for being a nominal variable.

Table 2. The results of the correlation analysis

	Statistical Indicators	Air tem.	Air vel.	MRT	Globe temp.
W/L	**Pearson C.**	**0.020**	**-0.323**	**0.057**	**0.063**
	Sig. (P-value)	**0.011**	**0.000**	**0.000**	**0.000**
W/H	**Pearson C.**	**0.056**	**0.028**	**0.168**	**0.160**
	Sig. (P-value)	**0.000**	**0.000**	**0.000**	**0.000**
P/H	**Pearson C.**	**0.043**	**0.511**	**0.120**	**0.099**
	Sig. (P-value)	**0.000**	**0.000**	**0.000**	**0.000**
Area	**Pearson C.**	**0.028**	**0.389**	**0.103**	**0.078**
	Sig. (P-value)	**0.000**	**0.000**	**0.000**	**0.000**
T_{gout}.	**Pearson C.**				**0.892**
	Sig. (P-value)				**0.000**
Air tem	**Pearson C.**				**0.736**
	Sig. (P-value)				**0.000**
Air vel.	**Pearson C.**				**0.003**

	Sig. (P-value)		**0.729**
MRT	**Pearson C.**		**0.981**
	Sig. (P-value)		**0.000**
Notes	**Sig. : indicates the statistical significance of correlation.**		
	Pearson C.: indicates the strength and direction of the relationship. Positive values indicate a positive association between variables and negative values indicate a negative association. Higher values indicate stronger impacts.		

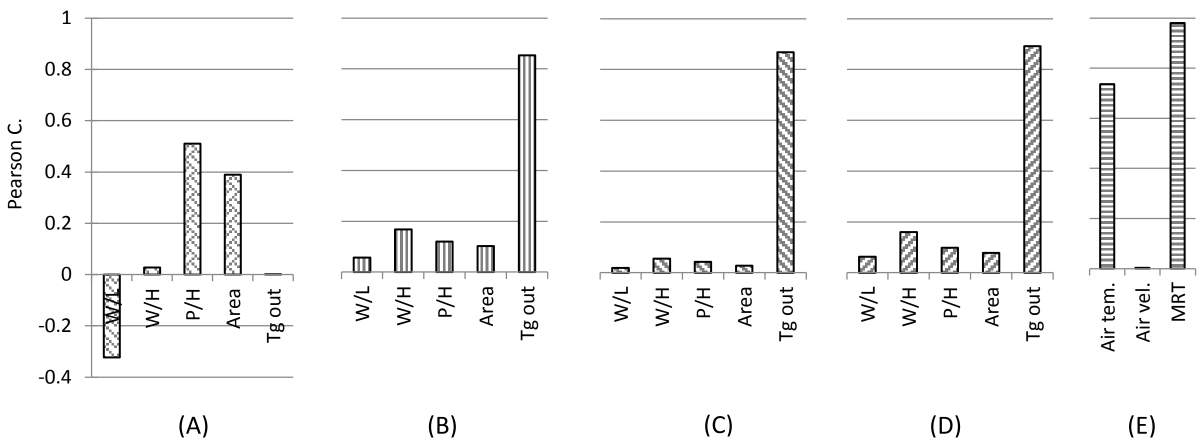


Figure 6. The significance of impact (Pearson C.) of each of the independent variables on Courtyards' air velocity (A), MRT (B), and Air temperature (C). The impact of the independent variables on thermal comfort (D) and the impact of mediating variables on thermal comfort (F)

Regarding the regression analysis, equation 3 was developed to predict people thermal sensation in any given courtyard space in Baghdad, or another location with similar conditions. The explanatory power of this equation (Adjusted R^2) is 0.818, which means that 81% of the variation in thermal sensation is explained by the considered variables. From this equation, it can be found that the stated most thermally efficient courtyard from the tested cases can provide thermal comfort if the outdoor Globe Temperature is equal to or less than 38 ^{o}C.

$$\text{Courtyard's } T_g = -24.142 + (-0.612 \times W/L) + (3.31 \times W/H) + (0.091 \times P/H) + (-0.12 \times Area) + (1.47 \times Out\ T_g) \quad \text{... (Eq3)}$$

3.3. Results discussion

These results highly agree with what has been concluded in previous literature. On the first hand, similar to this research, it has been concluded by many studies, such as (Aljawabra, 2014); (Ali-Toudert and Mayer, 2006); (Nasrollahi et al., 2017); (Berkovic et al., 2012) and (Nikolopoulou, 2011), that the MRT has the most significant impact on people thermal sensation in hot regions. Accordingly, having less exposure to the solar radiation and less surfaces radiation by having deeper and smaller courtyards will help to have more thermal comfort (Al-Hemiddi and Megren Al-Saud, 2001); (Muhaisen, 2006). This study results also agree with other studies, such as (Rajapaksha et al., 2002); (Soflaei et al., 2016) and (Mousli and Semprini, 2016), regarding the impact of courtyards' width and area on natural ventilation. However, a major difference compared with other studies can be found. Although the results agree with other studies, such as (Berkovic et al., 2012), in indicating a limited impact of natural ventilation on thermal comfort in courtyards, this may seem to imply a major contradiction with the majority of studies, which suggest that natural ventilation is a principal environmental strategy in courtyard buildings (Mousli and Semprini, 2016); (Shaheen and Ahmad, 2011b); (Ali and Shaheen, 2013b); (Agha, 2015). The answer is that this contradiction can be traced to the unrealistic design of openings in the courtyard cases used in the current study and in (Berkovic et al., 2012) study. In the current study, the cases used have no openings, while in (Berkovic et al., 2012) study, the cases have large opening allowed for solar radiation to access, not just air, which contributes to increasing the courtyards' temperature (Berkovic et al., 2012).

4. Conclusions & recommendations

The research presented in this paper did a simulation experiment to test courtyards' ability to provide thermal comfort. By taking Baghdad as a case study, it determined courtyards' efficiency in providing thermal comfort and the significance of the impact of each of the courtyards' design parameters on its thermal conditions. Furthermore, it defined the most effective factors on people thermal comfort in courtyard spaces, which all have not been determined in previous literature. The following conclusions and recommendations were drawn from this study's investigation:

1. Courtyards thermal efficiency increases by decreasing the ratios of W/H, W/L, P/H and the ground area, which means having deep and small courtyards.
2. As a semi-outdoor space, the impact of outdoor climatic conditions on courtyards' conditions significantly exceeds the impact of its design parameters.
3. The most effective design parameter on courtyards' air temperature and MRT is W/H ratio, while on air velocity, it is P/H.
4. The most effective climatic factor on people thermal sensation in courtyards is MRT.
5. The most effective design parameter on people thermal sensation in courtyard spaces is W/H ratio.
6. Regarding courtyard orientation, the results show that, for Baghdad and other similar locations, E-W and N-S orientations offer higher chances to provide thermal comfort than NW-SE and NE-SW.
7. The Globe Temperature difference between a properly designed courtyard and improperly designed one is around 20 ^{o}C. The highest decrease in Globe Temperature that the courtyard space can offer compared to outdoor temperature is around 4 ^{o}C during the day-time and 7 ^{o}C during the night-time.
8. Regarding providing thermal comfort, courtyards, without having any passive or active environmental support, cannot provide thermal comfort during summer in hot regions unless the outdoor Globe Temperature is equal to or below 38 ^{o}C.
9. For future research, this study recommends determining the impact of other effective factors on courtyards' performance, which might include vegetation and openings. The study also recommends determining the courtyard performance during the whole year and assessing its thermal efficiency using an adaptive comfort model developed for hot regions.

Acknowledgement

This paper has been conducted as a part of a PhD study sponsored by (HCED) in Iraq.

5. References

Agha, R. 2015. Traditional Environmental Performance: The Impact of Active Systems upon the Courtyard House Type, Iraq. *Journal of Sustainable Development,* 8**,** 28-41.

Al-Azzawi, S. H. A. 1984. *A descriptive, analytical and comparative study of traditional courtyard houses and modern non-courtyard houses in Baghdad:(in the context of urban design in the hot-dry climates of the sub-tropics).* University College London (University of London).

Al-Hafith, O., B K, S., Bradbury, S. & De Wilde, P. 2017a. The Impact of Courtyard parameters on its shading level An experimental study in Baghdad, Iraq. *Energy Procedia,* 134**,** 99-109.
Al-Hafith, O., Basavapatn, S., Bradbury, M.-S. & De Wilde, P. 2017. Thermally Comfortable Housing in Iraq – Prospects of the Courtyard Pattern in Achieving Energy Efficiency. 3rd International Sustainable Buildings Symposium, 2017b Dubai. Springers.
Al-Hafith, O., Satish, B., Bradbury, S. & De Wilde, P. 2017. Determining the courtyard thermal efficiency and its impact on urban fabric: A contextual study of Baghdad, Iraq. *In:* Brotas, L., Roaf, S. & Nicol, F., eds. PLEA 2017 - Design to Thrive, 2017c Edinburgh. NCEUB 2017, 3850-3858.
Al-Hemiddi, N. A. & Megren Al-Saud, K. A. 2001. The effect of a ventilated interior courtyard on the thermal performance of a house in a hot–arid region. *Renewable Energy,* 24**,** 581-595.
Al-Masri, N. & Abu-Hijleh, B. 2012. Courtyard housing in midrise buildings: An environmental assessment in hot-arid climate. Renewable and Sustainable Energy Reviews, 16, 1892-1898.
Al Horr, Y., Arif, M., KatafygiotouA, M., Mazroei, A., Kaushik, A. & Elsarrag, E. 2016. Impact of indoor
environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment,* 5**,** 1-11.
Al Jawadi, M. 2011. Model of House Design Responsive to Hot-Dry Climate. *International Journal for Housing Science and Its Applications,* 35**,** 171.
Aldawoud, A. & Clack, R. 2008. Comparative analysis of energy performance between courtyard and atrium in buildings. *Energy and Buildings,* 40**,** 209-214.
Ali-Toudert, F. & Mayer, H. 2006. Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and environment,* 41**,** 94- 108.
Ali, H., Turki & Shaheen, R., Bahjat 2013a. The Climatic Considerations for Planning & Architecture of the Traditional Arab City" Old City of Mosul, as a Model". *Al-Rafadain Engineering Journal,* 21**,** 20-32.
Ali, T. H. & Shaheen, B. R. 2013b. The Climatic Considerations for Planning & Architecture of the Traditional Arab City "Old City of Mosul, as a Model". *Al-Rafidain Engineering,* 21**,** 20-32.
Aljawabra, F. 2014. *Thermal comfort in outdoor urban spaces: The hot arid climate.* University of Bath.
Almhafdy, A., Ibrahim, N., Ahmad, S. S. & Yahya, J. 2015. Thermal performance analysis of courtyards in a hot humid climate using Computational Fluid Dynamics CFD method. Procedia-Social and Behavioral Sciences, 170, 474-483.
ASHRAE, A. 2005. Handbook of fundamentals. *American Society of Heating Refrigerating and Air Conditioning Engineers, Atlanta, GA*.
Bagneid, A. 2010. *The creation of a courtyard microclimate thermal model for the analysis of courtyard houses.* Texas A & M University.
Berardi, U. 2016. The outdoor microclimate benefits and energy saving resulting from green roofs retrofits.
Energy and Buildings, 121**,** 217-229.
Berkovic, S., Yezioro, A. & Bitan, A. 2012. Study of thermal comfort in courtyards in a hot arid climate. *Solar Energy,* 86**,** 1173-1186.
Bittencourt, L. & Peixoto, L. The influence of different courtyard configurations on natural ventilation through low-rise school buildings. Proceedings of the Seventh International IBPSA Conference, International Building Performance Simulation Association, 2001.
Chen, L. & Ng, E. 2012. Outdoor thermal comfort and outdoor activities: A review of research in the past decade. *Cities,* 29**,** 118-125.
Cho, S. & Mohammadzadeh, N. Thermal comfort analysis of a traditional Iranian courtyard for the design of sustainable residential buildings. 13th Conference of International Building Performance Simulation Association, 2013 France. 2327-2333.
Creswell, J. W. 2014. *Research design,* The UK, Sage publication.
De Dear, R. & Brager, G. S. 1998. Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions,* 104**,** 145-167.
De Dear, R. J. & Brager, G. S. 2002. Thermal comfort in naturally ventilated buildings revisions to ASHRAE Standard 55. *Energy and Buildings,* 34**,** 549–561.
Edwards, B. 2006. *Courtyard housing: Past, present and future,* The UK, Taylor & Francis.
El-Deep, K., El-Zafarany, A. & Sheriff, A. A. Effect of building form and urban pattern on energy consumption of residential buildings in different desert climate. PLEA 2012, 28th conference opportunities, Limits and needs towards an environmentally responsible architect lima, Peru, 2012.
El Harrouni, K. Thermal comfort in sustainable traditional courtyard house. The 2nd International Sustainable Buildings Symposium, 2015 Ankara- Turkey. Gazi University, 461-468.

Elaiab, F. M. 2014. *Thermal comfort investigation of multi-storey residential buildings in Mediterranean climate with reference to Darnah, Libya.* University of Nottingham.
Enescu, D. 2017. A review of thermal comfort models and indicators for indoor environments. *Renewable and Sustainable Energy Reviews,* 79**,** 1353-1379.
ENVI-MET. 2017. *ENVI-met 4. A holistic Microclimate Modelling System* [Online]. Germany: ENVI-MET GmbH. Available: http://www.model.envi-met.com/hg2e/doku.php [Accessed 09-05 2017].
Epstein, Y. & Moran, D. S. 2006. Thermal comfort and the heat stress indices. *Industrial health,* 44**,** 388-398. Fabbri, K. 2015. *Indoor Thermal Comfort Perception: A Questionnaire Approach Focusing on Children*, Springer.
Foruzanmehr, A. 2015. People's perception of the loggia: A vernacular passive cooling system in Iranian architecture. *Sustainable Cities and Society,* 19**,** 61-67.
Frontczak, M. & Wargocki, P. 2011. Literature survey on how different factors influence human comfort in indoor environments. *Building and Environment,* 46**,** 922–937.
Ghaffarianhoseini, A., Berardi, U. & Ghaffarianhoseini, A. 2015. Thermal performance characteristics of unshaded courtyards in hot and humid climates. *Building and Environment,* 87**,** 154-168.
Ghani, S., Elbialy, E. M. A. A., Bakochristou, F., Gamaledin, S. M. A., Rashwan, M. M. & Hughes, B. 2016. Thermal comfort investigation of an outdoor air-conditioned area in hot and arid environment. *Science and Technology for the Built Environment*.
Haberl, J. S. & Bou-Saada, T. E. 1998. Procedures for Calibrating Hourly Simulation Models to Measured Building Energy and Environmental Data. *Journal of Solar Energy Engineering,* 120**,** 193-204.
Hedquist, C., Brent, & Brazel, J., Anthony 2014. Seasonal variability of temperatures and outdoor human comfort in Phoenix, Arizona, U.S.A. *Building and Environment,* 72**,** 377-388.
Höppe, P. 2002. Different aspects of assessing indoor and outdoor thermal comfort. *Energy and Buildings,* 34**,** 661-665.
Jiang, C. 2017. *Improving Urban Climate Data Collection: Assessment and Redesign of Tsinghua's Meteorological Sensor Network.* Princeton University.
Kim, J. T., Lim, J. H., Cho, S. H. & Yun, G. Y. 2015. Development of the adaptive PMV model for improving prediction performances. *Energy and Buildings,* 98**,** 100-105.
Malekzadeh, M. 2009. *Positioning of outdoor space in house design-an energy efficiency and thermal comfort perspective.* © Masoud Malekzadeh.
Manioğlu, G. & Yilmaz, Z. 2008. Energy efficient design strategies in the hot dry area of Turkey. Building and Environment, 43, 1301-1309.
Martinelli, L. & Matzarakis, A. 2017. Influence of height/width proportions on the thermal comfort of courtyard typology for Italian climate zones. Sustainable Cities and Society, 29, 97-106.
Meir, I. A., Pearlmutter, D. & Etzion, Y. 1995. On the microclimatic behavior of two semi-enclosed attached courtyards in a hot dry region. *Building and Environment,* 30**,** 563-572.
Mohammed, M. I. 2010. The planning and design approaches to achieve the traditional principles of sustainability in the local modern housing architecture. *Journal of Engineering,* 16**,** 1034-1061.
Moosavi, L., Mahyuddin, N., Ab Ghafar, N. & Ismail, M. A. 2014. Thermal performance of atria: An overview of natural ventilation effective designs. *Renewable and Sustainable Energy Reviews,* 34**,** 654- 670.
Mousli, K. & Semprini, G. 2016. An Investigation of Natural Ventilation in a Courtyard House to Achieve Thermal Comfort in Hot-arid Climate. *9th International Conference on Indoor Air Quality Ventilation & Energy Conservation In Buildings.* Songdo, Republic of Korea.
Muhaisen, A. S. 2006. Shading simulation of the courtyard form in different climatic regions. *Building and Environment,* 41**,** 1731-1741.
Muhaisen, A. S. & B GADI, M. 2006. Shading performance of polygonal courtyard forms. *Building and Environment,* 41**,** 1050-1059.
Muhaisen, A. S. & Gadi, M. B. 2005. Mathematical model for calculating the shaded and sunlit areas in a circular courtyard geometry. *Building and Environment,* 40**,** 1619-1625.
Muhaisen, A. S. & Gadi, M. B. 2006. Effect of courtyard proportions on solar heat gain and energy requirement in the temperate climate of Rome. *Building and Environment,* 41**,** 245-253.
Nasrollahi, N., Hatami, M., Khastar, S. R. & Taleghani, M. 2017. Numerical evaluation of thermal comfort in traditional courtyards to develop new microclimate design in a hot and dry climate. *Sustainable Cities and Society*.
Nicol, F. 2004. Adaptive thermal comfort standards in the hot–humid tropics. *Energy and Buildings,* 36**,** 628–637.

Nicol, F., Humphreys, M. & Roaf, S. 2012. *Adaptive thermal comfort: principles and practice*, Routledge.

Nicol, J. F. & Humphreys, M. A. 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings,* 34**,** 563–572.

Nicol, J. F. & Roaf S. 2017. Rethinking thermal comfort. Taylor & Francis. NIKOLOPOULOU, M. 2011. Outdoor Thermal Comfort. *Frontiers in Bioscience,* 3**,** 1552-1568.

NikolopoulouI, M., Baker, N. & Steemers, K. 2001. Thermal comfort in outdoor urban spaces: understanding the human parameter. *Solar energy,* 70**,** 227-235.

Passe, U. & Battaglia, F. 2015. *Designing Spaces for Natural Ventilation: An Architect's Guide*, Routledge.

Rajapaksha, I., Nagai, H. & Okumiya, M. 2002. Indoor airflow behaviour for thermal comfort in a courtyard house in warm humid tropics. *Proceedings 'Indoor Air***,** 1072-7.

Ratti, C., Raydan, D. & Steemers, K. 2003. Building form and environmental performance: archetypes, analysis and an arid climate. *Energy and Buildings,* 35**,** 49-59.

Reiter, S. & De Herde, A. 2003. Quantitative and qualitative criteria for comfortable urban public spaces. *In:* Carmeliet, J., Hens, H. & Vermeir, G., eds. Research in Building Physics, 2003 Belgium. USA: CRC Press, 1001-1011.

Ridha, S. 2017. *Urban Heat Island mitigation strategies in an arid climate - Is outdoor thermal comfort reachable? (PhD thesis),* France, Toulouse University.

Rupp, R. F., Vásquez, N. G. & Lamberts, R. 2015. A review of human thermal comfort in the built environment. *Energy and Buildings,* 105**,** 178-205.

Salman, N. 2016. *Towards optimal design strategies in hot-arid climate.* Cardiff University.

Sadafi, N., Salleh, E., Haw, L. C. & Jaafar, Z. 2011. Evaluating thermal effects of internal courtyard in a tropical terrace house by computational simulation. Energy and Buildings, 43, 887-893.

Shaheen, B., R. & Ahmad, S., L., 2011a. The social - environmental and aesthetic integration in the designing of the multifamily housing developments: Evaluating the Iraqi experience. *The journal of engineering* 17**,** 156-176.

Shaheen, B., R. & Ahmad, S. L. 2011b. The social - environmental and aesthetic integration in the designing of the multifamily housing developments : Evaluating the Iraqi experience. *Journal of Engineering,* 17**,** 156-176.

SimonI, H. 2016. *Modeling urban microclimate: development, implementation and evaluation of new and improved calculation methods for the urban microclimate model ENVI-met.* Mainz, Univ., Diss., 2016.

Soflaei, F., Shokouhian, M., Abraveshdar, H. & Alipour, A. 2017. The impact of courtyard design variants on shading performance in hot-arid climates of Iran. *Energy and Buildings,* 143**,** 71-83.

Soflaei, F., Shokouhian, M. & Shemirani, S. M. M. 2016. Investigation of Iranian traditional courtyard as passive cooling strategy (a field study on BS climate). *International Journal of Sustainable Built Environment,* 5**,** 99-113.

Song, G. 2011. *Improving comfort in clothing*, Elsevier. Sthapak, S. & Bandyopadhyay, A. 2014. Courtyard houses: An overview. *Recent Research in Science and Technology,* 6**,** 70-73.

Taleghani, M., Kleerekoper, L., Tenpierik, M. & van den Dobbelsteen, A. 2015. Outdoor thermal
comfort within five different urban forms in the Netherlands. *Building and Environment,* 83**,** 65-78.

Toe, D. H. C. & Kubota, T. A review of thermal comfort criteria for naturally ventilated buildings in hot-humid climate with reference to the adaptive model. Conference Proceedings of the 27th International Conference on Passive and Low Energy Architecture, 2011. 13-15.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Methodological framework for evaluating liveability of urban spaces through a human centred approach

Daniele Santucci[1,2], Umberto Fugiglando[1], Xiaojiang Li[1], Thomas Auer[2] and Carlo Ratti[1]

[1] MIT Senseable City Lab, Cambridge MA, USA {danieles, umbertof, xiaojian, ratti}@mit.edu
[2] Technische Universität München, Chair for Building Technology and Climate responsive Design, Munich Germany {daniele.santucci, thomas.auer}@tum.de

Abstract: The quality of urban spaces is fundamental to the liveability of cities. In past decades, many studies at different scales have developed methodologies to evaluate comfort conditions in public spaces, as this aspect is essential for making cities more *walkable*. In this context, the present study develops a methodology for evaluating quality of cities through a dataset that collects millions of anonymous pedestrian trajectories through smartphone applications. This data, which includes about 1 million trips in the Boston area of over 60,000 anonymous users from May 2014 - May 2015, estimates human walking activities. Presence is used as an indicator for walkability by relating it to additional layers to provide an accurate model of the urban morphology. The aim of this paper is to present a case study on how human walking activities can be sensed, quantified and applied to determine the impact of the urban morphology and its effects on climate at a micro-scale. This study also reveals how people flows react to highly fluctuating microclimatic conditions and how pedestrians respond to the variability of the urban environment. Together, these approaches will affect multiple aspects of human life including health and wellness, infrastructure and quality of life in cities to create liveable and healthier cities.

Keywords: liveable urban spaces, data mining, environmental quality, outdoor thermal comfort.

1. Introduction

Keeping citizens in a healthy state is a goal every society should achieve. For achieving this challenging target, walking can be considered as one of the fundamental activities as it is a significant indicator of a healthy population (Ewing and Handy, 2009; Yin et al., 2016). Moreover, walking is possible if conditions are comfortable and safe, if the environment is attractive and if relevant places and activities are reachable.

Therefore, understanding the relationship between the urban built environment and physical activity is a high priority for design and planning (Christian et al., 2011).

Besides this aspect, shared public spaces make urban life distinctive and differentiated.

For administrators, policy makers, designers and planners, it is crucial to determine effective performance indicators to predict and evaluate environmental quality and implement the gathered information into design and planning decisions. This aspect is fundamental since the usage of public realm is the most relevant measure to evaluate its performance and for guaranteeing continuity through time.

Summarizing, walking can be used as an indicator for the quality and attractiveness of the urban environment, using humans as sensors.

This paper, part of a wider research project, attempts to quantify a relation between people's presence and the urban morphology with a human centred approach.

Through data mining individuals can become the main experimental subjects: using data of individuals allows developing a personal comfort model that predicts individual responses also on a large sample. Personal comfort models are usually based on a small number of individual surveys. In this study, we are using a Big Data approach using signals collected from a sensed environment.

Following this premise, this study uses human response for predicting the quality of comfort conditions in public spaces, and not with a simulation-based method.

For reaching this aim, we use walking data collected over a period of one year – from May 2014 to May 2015 – in the Greater Boston area. The dataset, which consists of 250.000 anonymous pedestrian trajectories collected through smartphone applications, records human walking activity.

1.1. Methodology

The data reveal patterns of how people use public spaces for walking in a high spatiotemporal resolution. Presence is used as an indicator for walkability and, more in general, to estimate the quality and the characteristics of the urban environment. In order to relate walking behaviour to form and its effects, we use the Sky View Factor (SVF) as an indicator of the urban morphology. The SVF is an index that allows determining a variety of parameters such as density, typological variety, and the exposure to the environmental conditions (Carrasco-Hernandez et al., 2015).

Several studies have demonstrated the relevance of the SVF in characterizing both microclimatic conditions, as peak temperature difference can be assessed in terms of height-to-width ratios or sky view factors (Oke, 1987), and comfort, as environmental stimulation is an issue of primary importance in external spaces (Nikoloupoulou et al., 2003)

The novelty of this study is to evaluate the dependency between walking activity and climatic conditions at a micro-level using the SVF as a fundamental indicator to identify spatial patterns of environmental diversity at the urban scale depending on seasonal climatic variations. SVF variability corresponds to the diversity of the built environment and therefore to diverse microclimatic conditions: variant urban environments generate varying comfort conditions in space at the street level. Since complex urban morphology generates environmental diversity, this correlates with freedom of choice and an overall expression of comfort (Steemers and Ramos, 2010).

1.2. Previous work

The past work the has been dedicated to the relation between microclimate and people's presence, basing the observation on outdoor comfort mapping using the Universal Thermal Climate Index (UTCI) and relating it to people's presence with different techniques (Chokhachian et al., 2017a). These studies associate field measurements and simulations reaching a high mapping resolution modelled on small samples. Mapping outdoor thermal comfort, which is a complex, subjective human sensation, can be combined with a different perspective, in particular to increase the scale to the urban dimension.

Furthermore, the most used indices to map outdoor comfort such as Physiological Equivalent Temperature (PET), Perceived Temperature (PT) and Universal Thermal Climate Index (UTCI) are expressed as an equivalent temperature that describes how a human would physiologically react to a given set of environmental conditions (Reinhart et al., 2017). UTCI is based on a 187 node model (Fiala et al., 2012. Kampmann et al., 2011) and has been shown to be able to detect potential human discomfort under larger sets of microclimatic conditions than other biometeorological indices (Blazejczyk et al., 2012). In recent years, computational models of environmental processes have been developed in order to use UTCI predictions to design more comfortable outdoor spaces (Matzarakis et al., 2010).

The remaining question is to which extent those indices are able to predict occupancy patterns in public outdoor spaces, due to the resolution that they are able to depict (Reinhart et al., 2017). In fact, these studies show some limitations in terms of scale since the increase of scale corresponds to a decrease in terms of accuracy: either the granularity is very high – up to 1 m – and the model scale is limited to a few blocks, or, to enlarge the observation scale, the resolution drastically decreases.

Furthermore, only few studies have explored the physiology of human comfort in outdoor environments: the physiological response can only partially explain comfort perception in the urban environment (Steemers and Ramos, 2010).

2. Analysis

Using a large dataset of around 250.000 individuals' walking trajectories allows providing a data driven methodology that combines a high accuracy in terms of spatiotemporal distribution in relation to a wider observation scale that more globally illustrates the dependency between walking activity and microclimatic conditions for an entire city area. To accomplish this objective, we analysed the distribution of walking activity and its variations in relation to strongly different climatic conditions, for providing a useful design tool for any urban intervention that aims at improving outside comfort conditions with larger effects on the population.

2.1. Study area

As the largest city in Massachusetts, the city of Boston was chosen as the study area. Boston has land area of 106.7 km^2 and total population of 670,000 in 2016.

Fig. 1: Study area with highlighted trajectories

Due to its compact structure, Boston is one of the most *walkable* cities in the United States (Vanky et al., 2017).

2.2 Dataset

The datasets used in this study include anonymous human trace data, Google Street View (GSV) and Open Street Map (OSM) data.

The anonymous human trace data was collected from activity-oriented mobile phone application. The data, which include about 1 million trips of over 60,000 anonymous users from May 2014 – May 2015, record GPS locations and walking behaviour of anonymous individuals in the Boston metropolitan area.

The available data differ from month to month, with no evident reason: 33,114 trajectories were recorded in September 2014, while in February 2015 only 19,302. This difference is not only related to weather conditions, since hot months such as May, June, July and August have less records than February.

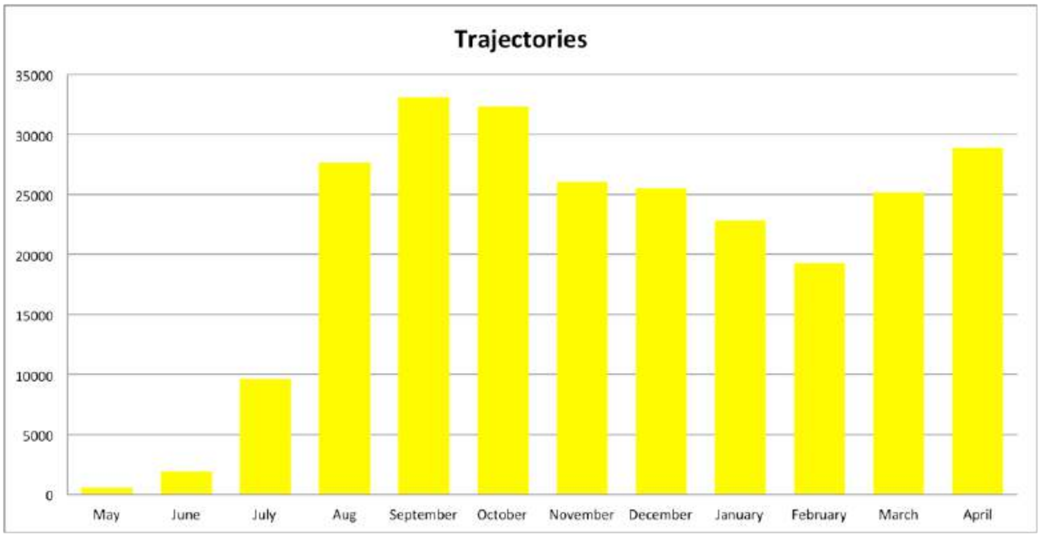


Fig. 2: Monthly distribution of the trajectories

Due to the noise of the original GPS locations, the data were normalized using a map-matching algorithm based on the Open Street Map to rectify those mistaken trajectories. In this study, we used the Hidden Markov Map Matching algorithm (HMM) to match the measured longitudes/latitudes in human trace records to roads (Newson and Krumm, 2009). The HMM algorithm accounts for the GPS noise and the layout of the road network, and matches the GPS locations to corresponding streets with very good accuracy.

The GSV data were used to measure and estimate the geometries of street canyons and the amount of street greenery. Since GSV panoramas are distributed discretely along streets, we first created samples every 100m along the streets in the study area. Based on those created samples, we further downloaded the GSV images based on the Google Street View API (Google, 2016; Li et al., 2018).

The GSV images and the walking trajectories matched with the OSM street segments have a complete correspondence in space since they are both located at the street centreline. The datasets allow generating a georeferenced occupancy study in relation to the sky view factor (SVF) that quantifies the degree of sky visibility and therefore the proportions of street canyons. Previous studies have shown that the enclosure of street canyons is related to human perception of the environment (Asgarzadeh et al., 2014; Li et al., 2015) and the walkability of the streets (Yin and Wang, 2016).

2.3 Climate analysis

Additionally, we analysed weather data for the same time period May 2014 until May 2015 using Weather Underground hourly data records retrieved from the KBOS station (Boston Logan Airport) to classify daily conditions and cluster them into typical days categories, as in Table 1.

After selecting the most representative days for each season in terms of Air Temperature, Relative Humidity, Wind speed and Wind direction that are considered typical in relation to the season's averages, we identified the highest concentration of hot days, including the hottest day of the year 2014 (September 2nd) in September, whereas February 2015 was the coldest month (including the coldest days, February 15th and 16th).

This classification was used as a fundamental clustering of mesoclimatic conditions throughout the year corresponding to the available human trace data.

Table 1: Climate data classification

Hot	**Average**	**Cold**
Hot and humid	Average humid	Cold and humid
Hot and dry	Average dry	Cold and dry
Hot peak		Cold peak

3. Results

3.1. Trajectories' distribution

In a first phase, we carried out a quantitative analysis of the trajectories in terms of length and street segments. As outlined in §2.2, GPS positions recoded by the phone app were matched to street segments in the OSM database: specifically, each trajectory can be considered as a list of street segments, which are identified by unique codes called OSM IDs.

In Fig. 3, trajectories are grouped according to their length in meters (considering stepping intervals of 200m) and their normalized frequencies (counts) are plotted. Trajectories were also divided between weekdays and weekends in order to highlight potential specific patterns assuming different behaviours during working and leisure routines. The resulting graphs show very similar patterns: the subdivision in weekdays and weekends does not show substantial differences. Similar are also the distributions of the cold and hot period.

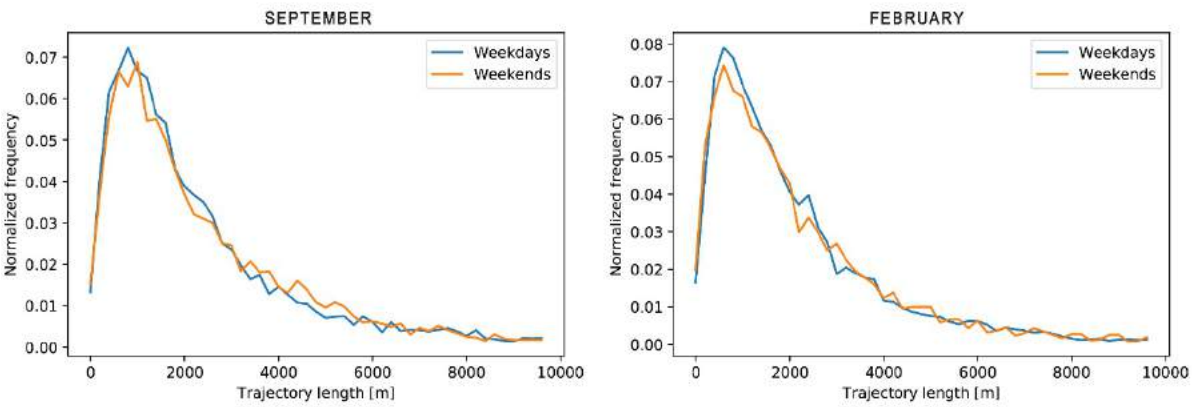


Fig. 3: Frequency of trajectory lengths.

Moreover, an analysis of the most frequent street segments (OSM IDs) has been carried out throughout all the trajectories in the database. Fig. 4 shows the total counts of the first 100 most frequent street segments, ordered by their rank. The different ordinate's axis scale is due to the fact that the total number of trajectories in February is approximately double of the one for the trajectories in September.

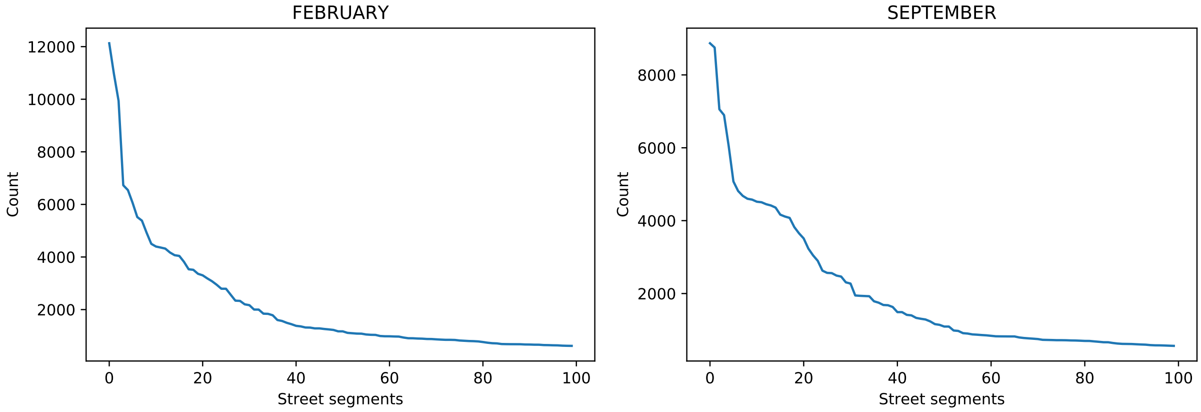


Fig. 4: Total counts of the first 100 most frequent street segments.

The similar distribution can be referred to a certain continuity in patters of urban occupancy: besides varying seasonal climatic conditions, specific routes maintain their qualities besides meteorological variations: people rather adopt different clothing insulation than drastically changing their walking habits.

3.2. Sky view factor variability

To further investigate people's response to microclimatic conditions and for finding correlations between varying weather conditions and trajectories' length and location, a streetscape variable was selected – street enclosure by buildings – to identify a parameter that corresponds to diverse outdoor comfort conditions.

Numerous studies have already demonstrated that the sky view factor (SVF) can be a representative indicator for urban building density and layout. SVF is the ratio of the radiation received (or emitted) by a planar surface to the radiation emitted (or received) by the entire hemispheric environment and it affects urban radiation exchange and urban microclimate (Watson and Johnson, 1987). Several others have related the effects of SVF to thermal comfort in the urban environment (Mayer et al., 1987; Lin et al., 2008/2011; Bröde et al., 2012).

Under this premise, the SVF is considered to be a fundamental parameter in order to evaluate microclimate in urban space as it has been demonstrated that the correlation between SVF and outdoor thermal comfort (mean radiant temperature) is particularly strong, in particular for dense urban environments (Wang et al., 2014).

In this section, we analyse the variability of microclimatic conditions through the variability of the SVF. As explained in §2.2, SVF sampling points on the streets (obtained combining different GSV pictures) are uniformly distributed every 100m in the urban environment. We therefore compute for each street segment the standard deviation of the corresponding SVFs, assigning a value equal to zero to the segments that contain only one SVF sample. The SVF variability (in terms of standard deviation) is then compared to the total frequency of the street segments (as calculated in Fig.4). In Fig. 5, each plotted point represents a street segment, along with its frequency count and the standard deviation of its SVFs.

In order to investigate a possible relation between the street segment frequency and the SVF's variability, a linear regression model has been fitted to the data. The regression line is plotted in Fig. 5, and a positive linear dependency has been found between the SVF standard deviation and the street segment frequency. In fact, the null hypothesis on the regression line's coefficient equal to zero can be rejected through a t-test with a significance level of 1.6% and 3.8% for respectively February and September.

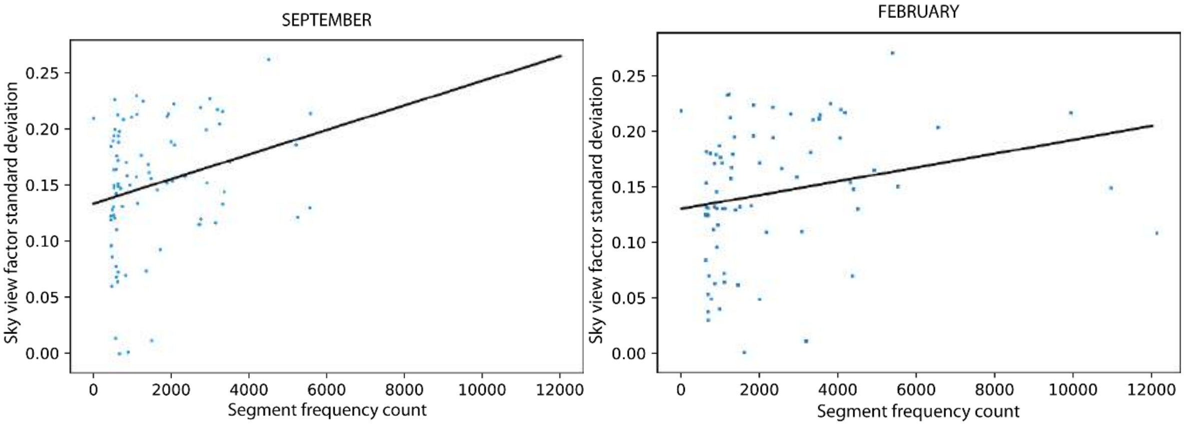


Fig. 5: SVF Standard deviation and street segment frequency

4. Conclusions

4.1. Outlook

The present study provides a global mapping that illustrates to which extent pedestrians respond to the variability of the urban environment. The correlation between the SVF and the frequency of pedestrian activity along a street segment shows strong relations between the variability of urban spaces and their attractiveness for pedestrian use.

This result can be associated to the concept of diversity of cities that Jane Jacobs (Jacobs, 1961) considered one of the most important indicators for urban vitality.

Furthermore, a higher variance of the SVF corresponds to a higher variability of the microclimatic conditions, producing frequent differences and variations in terms of outdoor comfort conditions: people preferably walk where the urban morphology determines variant microclimatic conditions. From a physiological point of view, sudden changes do not immediately provoke skin temperature shifts (Chokhachian et al., 2017b; Parkinson et al. 2012).

This tendency is valid under highly different climatic conditions, both for cold periods as well as for hot ones. The large number of trajectories and the urban scale allow considering this relation as an effective indicator for planners and policy makers with potentially extensive design implications.

For extensively representing the variance of the urban morphology, multiple additional layers, such as sidewalk area, population and building density, will be integrated to the model to support the assumption that variability in urban morphology generates more liveable urban environments.

4.2. Limitations

The first limitation of the study is given by the dataset characteristics, which might not represent a large population. Compared to similar studies that have been developed in the last decades, the sample includes a larger number of subjects: interview-based studies have usually been transversal with the number of subjects varying from 91 to 2700, some longitudinal studies were conducted with in between 8 and 36 subjects (Reinhart et al., 2017).

Besides this, the amount of trajectories varies every month, without any demonstrable reason. The data, that was made anonymous, do not allow discerning between fluctuating individual walking activity and irregular use of the activity-oriented mobile phone application. The different amount of trajectories could be related both to less application users as well as to less walking activity. Due to this reason, in the presented study trajectories frequencies were normalized.

Finally, the availability of the data from GSV images for gathering the SVF was not fully covering the entire area. The SVF information is available for a percentage between 74 and 85 of the analysed OSM street segments depending on the observed month.

However, this study focuses on the variability of microclimatic conditions and does not map the equivalent temperature for each time-stamp and location, as this process would be too time and resources intense.

4.3. Future work

To obtain more solid results, the missing months will be analysed following the outlined methodology.

In an upcoming phase, the results will be validated through different methods; in space, the outdoor comfort conditions will be mapped using the UTCI model. The most frequented segments will be included in a microclimatic model to verify the relevance of the SVF in terms of exposure to environmental factors, in particular how strong it influences the mean radiant temperature and its effects on the equivalent temperature. In time, the trajectories will be framed with a more detailed temporal distribution.

Scaling down to a higher resolution will allow evaluating each individual trajectory, and not limiting it to the most frequented street segments. This process will take also into account the thermal history of people and the path finding theories to more accurately describe sequences and the impact of variance.

5. Acknowledgements

The authors would like to thank Cisco, SNCF Gares & Connexions, Brose, Allianz, UBER, Fondation OCP, Liberty Mutual, Ericsson, Saudi Telecom, Volkswagen Group America, Philips, Austrian Institute of Technology, Fraunhofer Institute, Kuwait-MIT Center for Natural Resources, SMART—Singapore MIT Alliance for Research and Technology, AMS Institute Amsterdam, Victoria State Government, and all the members of the MIT Senseable City Lab Consortium for supporting this research. We further want to thank the Institute of Advanced Studies of Technical University of Munich for supporting the research exchange.

6. References

Asgarzadeh, M., Lusk, A., Koga, T., & Hirate, K. (2012) Measuring oppressiveness of streetscapes. Landscape and Urban Planning, 107(1), 1–11.

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., Tinz, B. (2012) Comparison of UTCI to °Cselected thermal indices, Int. J. Biometeorol. 56 (2012) 515–535.

Bröde, P., Błazejczyk, K., Fiala, D., Havenith, G., Holmér, I., Jendritzky, G., Kuklane, K.,Kampmann, B. (2013) The Universal Thermal Climate Index UTCI compared to ergonomics standards for assessing the thermal environment, Industrial Health, 51(1):16-24

Carrasco-Hernandez, R., Smedley, A.R.D., Webb, A. R. (2015) Using urban canyon geometries obtained from Google Street View for atmospheric studies: Potential applications in the calculation of street level total shortwave irradiances. Energy and Buildings 86 (2015) 340–348.

Chokhachian, A., Santucci, D., Auer, T. (2017a) A Human-Centred Approach to Enhance Urban Resilience, Implications and Application to Improve Outdoor Comfort in Dense Urban Spaces. Buildings 2017, 7, 113.

Chokhachian, A., Santucci, D., Vohlidka, P., Auer, T. (2017b) Framework for Defining a Transient Outdoor Comfort Model in Dense Urban Spaces, Processes & Findings. 7th International Conference Architecture and Urbanism - Contemporary research, Prague.

Christian, H. E., Bull, F. C., Middleton, N. J., Knuiman, M. W., Divitini, M. L., Hooper, P., & Giles- Corti, B. (2011). How important is the land use mix measure in understanding walking behaviour? Results from the RESIDE study. International Journal of Behavioral Nutrition and Physical Activity, 8(1), 55.

Ewing, R., & Handy, S. L. (2009). Measuring the unmeasurable: Urban design qualities related to walkability. Journal of Urban Design, 14, 65-84.

Fiala, D., Havenith, G., Bröde, P., Kampmann, B., Jendritzky, G. (2012) UTCI-Fiala multi-node °Cmodel of human heat transfer and temperature regulation, Int. J. Biometeorol. 56 (2012) 429–441.

Google, 2016. Google Street View Image API. https://developers.google.com/maps/ documentation/streetview/ (accessed October 2016).

Jacobs, J. (1961) The death and life of great American Cities. Random House, New York [The Modern Library, New York, 1993].

Jendritzky, G., Havenith, G., Weihs, P., Batchvarova, E. & Dedear, R. (2007) The Universal Thermal Climate Index Utci Goal And State Of Cost Action 730. 12th International Conference On Environmental Ergonomics.

Kampmann, B., Brode, P., Jendritzky, G., Fiala, D., Havenith, G. (2011) The Universal °CThermal Climate Index UTCI for assessing the outdoor thermal environment, 4th Int. Conf. Human-Environment Syst. Japan, 2011.

Li, X., Zhang, C., Li, W., Ricard, R., Meng, Q., & Zhang, W. (2015) Assessing street-level urban greenery using Google Street View and a modified green view index. Urban Forestry & Urban Greening, 14(3), 675-685.

Li, X., Santi, P., Courtney, T., Verma, S., Ratti, C. (in review) Investigating the association between streetscape built environment and human walking activities using human trace data. Transactions in GIS.

Lin T-P, Matzarakis A (2008) Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. Int J Biometeorol 52:281–290.

Lin T.-P., Matzarakis A., (2011) Estimation of outdoor mean radiant temperature by filed experiment and modelling for human- biometeorology use. In: Proceedings of the 11th annual meeting of the European Meteorological Society, Berlin, Germany, 9.19–22 2011 European Meteorological Society, EMS2011–2089.

Matzarakis, A., Rutz, F., Mayer, H. (2010) Modelling Radiation fluxes in simple and complex °Cenvironments – basics of the RayMan model, Int. J. Biometeorol. 54 (2010) 131–139.

Mayer, H., and P. Höppe (1987) Thermal Comfort of Man in Different Urban Environments. Theoretical and Applied Climatology 38 (1): 43–49.

Newson, P., & Krumm, J. (2009) Hidden Markov map matching through noise and sparseness. In Proceedings of the 17th ACM SIGSPATIAL international conference on advances in geographic information systems (pp. 336-343). ACM.

Nikolopoulou, M., Steemers, K. (2003) Thermal comfort and psychological adaptation as a guide for designing urban spaces, in Energy and Buildings 35 (2003) 95–101

Oke, T. (1987) Boundary Layer Climates, Routledge, London

Parkinson, T., de Dear, R., Candido, C. (2012) Perception of Transient Thermal Environments: pleasure and alliesthesia. Proceedings of 7th Windsor Conference, Windsor, UK, 2012

Reinhart, C. F., Dhariwal, J., Gero, K. (2017) Biometeorological indices explain outside dwelling patterns based on Wi-Fi data in support of sustainable urban planning. Building and Environment 126 (2017) 422–430.

Steemers, K., Ramos, M. (2010) Urban Environment Diversity and Human Comfort, in *Designing High-Density Cities for Social and Environmental Sustainability,* Edited by Edward Ng, UK and USA in 2010

Vanky, A.P., Verma, S. K., Courtney, T. K., Santi, P., Ratti, C. (2017) Effect of weather on pedestrian trip count and duration: City-scale evaluations using mobile phone application data, Preventive Medicine Reports, Volume 8, 2017, Pages 30-37, ISSN 2211-3355, https://doi.org/10.1016/j.pmedr.2017.07.002.

Wang Y., Akbari H. (2014) Effect of Sky View Factor on Outdoor Temperature and Comfort in Montreal. Environmental Engineering Science. June 2014, 31(6): 272-287.https://doi.org/10.1089/ees.2013.0430.

Watson, I.D., and Johnson, G.T. (1987). Graphical estimation of sky view—factors in urban environments. J. Climatol. 7, 193.

Yin, L., & Wang, Z. (2016) Measuring visual enclosure for street walkability: Using machine learning algorithms and Google Street View imagery. Applied Geography, 76, 147-153.

SPECIAL SESSION

ASHRAE Global Thermal Comfort Database II

Invited Chair:
Richard de Dear

WORKSHOP 4

The Diversity Factors

Invited Chairs:
Dolaana Khovalyg and Fergus Nicol

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Responses of German subjects to warm-humid indoor conditions

Michael Kleber and Andreas Wagner

Building Science Group, Faculty of Architecture, Karlsruhe Institute of Technology, Englerstr. 7, 76131 Karlsruhe, Germany, kleber@kit.edu

Abstract: In summer of 2016 and 2017 experiments with a total of 300 participants have been conducted in a German test facility. Each participant experienced two out of nine different combinations of operative temperature (26°C, 28°C, 30°C) and relative humidity (50%, 65%, 80%) in order to examine an elevated humidity ratio between 10 and 21 g/kg. Questionnaires were filled out in specific intervals and certain physiological parameters have been measured continuously. The subjects wore their own summer clothing (average clo = 0.50, SD 0.09) and were recruited from male and female persons in two age groups: 18 to 32 years and 50 to 80 years. Results indicate that responses are dependent on both temperature and humidity as well as on other factors like thermal history. A linear regression model using operative temperature and humidity ratio is presented to describe the percentage of acceptability and is used to derive an extended comfort zone for seated activity in summer conditions (met = 1.1 and clo = 0.5). Different responses are compared to ones of other studies. Thermal acceptability for example proves to be significantly lower with the German subjects than with participants who are adapted to a hot-humid climate. PMV shows overestimation of thermal sensation at the lower temperatures and underestimation at the higher ones.

Keywords: laboratory study; warm-humid environment; thermal comfort; thermal acceptability; humidity sensation

1. Introduction

Thermal comfort at higher temperatures and elevated humidity has been an issue of several studies so far. It has to be differentiated between hot temperatures, which have been examined often in relation to extreme working conditions (firemen, steel workers, soldiers in hot climate) (Mehnert et al, 2000) (Shi et al, 2013), and warm temperatures, which have been subject of investigation in relation to outdoor climate and indoor climate of free-running buildings (Feriadi et al, 2004) (Djamila et al, 2013). With regard to the latter, after Fanger, who raised humidity up to 70% in his experiments (Fanger, 1970), studies used humidity levels of 80% and even 90% relative humidity (Toftum et al, 1998) (Kitagawa et al 1999). The temperatures were in the range from 26°C to 36°C. Relevant studies are listed in (Fountain et al, 1999), (Jin et al, 2017) and (Kleber et al., 2018).

Upper limits for humidity in the summer period play a role in building standards, which define comfort criteria for mechanically ventilated and air-conditioned buildings. The current definition in ASHRAE 55-2017 continues using a humidity ratio of 12 g/kg. This limit is relevant, if the “Graphic Comfort Zone Method” (two comfort zones for 0.5 and 1.0 clo in relation to operative temperature and humidity ratio) is applied. If the “Analytical Comfort Zone Method” is used, with moderate temperatures the humidity ratio is allowed to rise up to 21 g/kg. The European standard EN 15251 limits the humidity ratio to 12.0 g/kg whereas the German national annex specifies 11.5 g/kg and 65% RH, respectively. Different reference figures had been used in ASHVE/ASHRAE: dew point, vapour pressure, wet bulb globe temperature, relative humidity and humidity ratio. In a withdrawn German DIN standard relative humidity had been used; in the European standard EN 15251 humidity ratio is applied like in the current ASHRAE 55-2017. Studies with regard to higher temperatures found best correlation with enthalpy (Fang et al, 1998) (Shi et al, 2013), others suggested effective temperature (Jing et al, 2013) (Zhai et al, 2015).

Human response to conditions above the usual comfort zone is important because the combined effect of temperature and humidity increases discomfort due to blocking the evaporative heat loss through sweating and the respiratory system (Toftum et al, 1998). The above-mentioned studies were mostly performed in regions, which already have a warm-humid or hot-humid climate. However, the topic is also of interest in other countries, because - induced by climate change - the outdoor conditions are supposed to become warmer as well as more humid and more extreme weather situations (like thunderstorms) are predicted to occur.

In Germany no laboratory study under warm-humid conditions was known yet, but within the subtask of a recent research project it was possible to conduct such experiments with a large number of participants. Main objective of this project was to examine if with elevated temperatures there would be evidence for a certain fixed limit of humidity ratio (like 12.0 or 11.5 g/kg defined in EN 15251 or its German addendum respectively). The important issue of which simple humidity measure best representing the impact on the user was addressed, too.

According to the available budget in this project, a large sample size had been strived to enable cross-checking the influence of other variables on thermal sensation, especially at the elevated level of temperature and humidity. Gender, weight and age are personal characteristics, which had been researched in many studies. As PMV is widely used as a standard measure to rate indoor conditions, thermal sensation responses in this study were also compared to this index. With regard to the adaptive approach the impact of the subject’s thermal history (outdoor climate) was included in the investigation.

2. Methods

In order to investigate the relevant aspects described above, a large experimental study was performed in a test facility at the Karlsruhe Institute of Technology (KIT). This section provides information about the facility, the experimental procedure and the statistical methods, which have been applied.

2.1. Test facility

The “Laboratory for Occupant Behaviour, Satisfaction, Thermal comfort and Environmental Research (LOBSTER)” at KIT holds two almost identical rooms, of which five surfaces can be separately conditioned (heated or cooled) by a capillary system. The sixth surface (window façade) is highly insulated with 3-pane glazing and vacuum insulation in the balustrade. By two convectors per room the supply air can be conditioned, too. Thereby, a very accurate and uniform control of operative temperature is possible. A humidifying function was subsequently installed by means of two circulation humidifiers (evaporative) per room. They were placed in a housing to hide them from the participants and to reduce the noise level to a minimum. A further detailed description of the test facility at KIT can be found in (Wagner, 2018).

2.2. Experimental Design

The total study comprised 328 participants, of which 28 took part in a pilot study in October 2015. The main studies took place in summer 2016 (136 participants) and summer 2017 (164 participants). Participants were recruited via the Internet and a local weekly paper and were remunerated afterwards. Two age groups (18 to 32 years and 50+ years) took part, and both groups were comprised of both female and male participants. All experiments had been approved by the ethics and the data protection commissions of KIT.

To span a range of humidity ratio around the mentioned values of 11.5 and 12.0 g/kg and up to high humidity of 21 g/kg nine different test conditions were defined. They were set up by a matrix of operative temperatures (26°C, 28°C and 30°C) and relative humidity (50%, 65% and 80%). A participant randomly experienced two out of those nine conditions for 60 minutes each. During that time skin temperature, skin wettedness and heart rate were measured continuously. The subjects had been asked to wear their own summer clothing (possibly cotton and no synthetic material) and were allowed to change their clothes if they wanted to. This optional change of clothes was tracked by questions in the questionnaire.

The experiments took place weekdays in the morning (9:30 until 12:30) or in the afternoon (13:00 until 16:00). Each person participated just once to avoid carry-over or learning effects. After 30 minutes in the vestibule for acclimatization, attaching sensors and filling a first questionnaire, the participants entered room "A" to spend one hour under condition 1 (Figure 1). Right after entering and taking the seat at the desk, a first short questionnaire had to be completed. The short questionnaire had to be repeated after 15 and 30 minutes. After an attendance of 60 minutes a long questionnaire showed up on the screen. After completing this, the participant changed directly to the second room ("B") and the described procedure was repeated under condition 2.

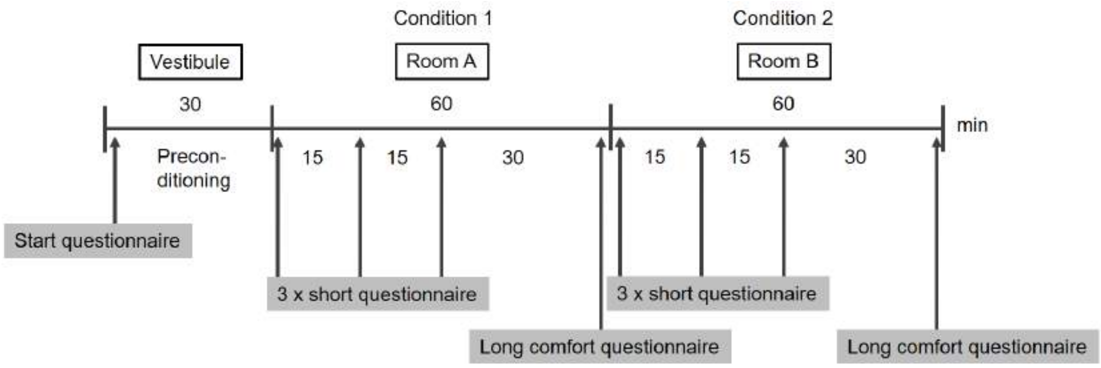


Figure 1. Experimental procedure, which each participant experienced one

During the experiment, the participants were asked to stay seated at the desk and fill the questionnaires at the computer. The "short questionnaire" comprised 14 questions on thermal comfort, air quality, sweat sensation and on the fact, if clothing was changed. The standard thermal comfort questions (TSV 7-point-scale, TPV 5-point-scale and TCV 4-point-scale) were supplemented by humidity aspects (HSV 7-point-scale, HPV 5-point-scale and HCV 4-point-scale). General room climate acceptance (4-point-scale), perceived air quality (0-100), perceived air cleanness (0-100), thermal acceptance (4-point-scale and continuous scale) and humidity acceptance were included as well. One last question asked for sweat sensation at ten different body parts and if sweating there was annoying.

In the "long questionnaire" aspects about air movement sensation, the participant's current activity, the perceived impact of the room condition, humidity sensation at five body parts (skin, eyes, nose, mouth) and about terms describing the current situation were added. In total it comprised 32 questions.

2.3. Statistical methods

As this study mainly intends to find interrelations between temperature and humidity on the human thermal comfort, correlation and regression were used to find and describe their possible impact. It was found that multiple linear regression models were mostly sufficient to describe the relevant relations. In most cases polynomial or quadratic regression did not significantly improve the results. However, polynomial regression was used when it was originally applied in a comparative study (cf. section 3.4).

The study was originally planned as a “between-subjects-design” to avoid learning effects and to hamper demotivation of the participants if experiencing in total nine conditions. Therefore a large sample size was needed (target: 30 participants per condition). For gaining additional experience on the impact of a step change and for making use of the second conditioned room, it was decided to test each participant also in the second condition. As a consequence the setup became a complex design, for which the “between-subjects-design” methods are not applicable. Therefore in the analysis either only one condition per person was used or methods of mixed-effect-models were applied.

For creating percentages of a special vote being selected, the whole sample had been clustered into groups and the proportion of participants in each group was calculated. The groups were created differently (cf. Table 4, section 3.2), but always in a way that only one vote per person (between-subjects-design) was included into the analysis. In the “Results” section analysis of grouped responses is marked as “Averaged votes” in opposite to “Single votes”.

Statistical analysis was conducted with SPPS and R. The freely available software R was also used for calculating comfort indices via a package called “comf” (Schweiker, 2016).

3. Results

Based on the large sample and the extensive questionnaires, analysis was conducted concerning various aspects. As no significant influence of gender and age was found in this study, the sample was used as a whole. The article focuses on the role of humidity and its impact against the background of the definition in standards. This section first describes and rates possible measures to be integrated into models for prediction; afterwards thermal acceptability is analysed and used to derive an extended comfort zone. Two models for predicting thermal sensation vote (TSV) are described and the influencing variables are discussed. Finally, results of this study are compared to PMV and to results of other studies.

3.1. Humidity related indicators

Not only in the standards (cf. section 1) there have been changing measures to rate the humidity level sensed by and affecting on the human body. But also in literature experiments and discussions can be found, which favour the one or the other.

Against this background the responses to humidity sensation (HSV) have been analysed on the base of different independent variables, which are all measures of humidity or temperature and humidity combined. In this case a second-degree polynomial regression model performed slightly better than a linear one. Table 1 displays the adjusted coefficients of determination for relative humidity (RH), dew point (DP), enthalpy and humidity ratio (HR). It can be stated that relative humidity is not a good predictor at all, but the other three variables lie within a similar range. In the second condition generally HSV is stronger influenced by humidity; with enthalpy the adjusted R^2 even reaches 0.986.

When regarding the coefficient of determination for a model with HR as predictor and based on single votes at operative temperatures below 27°C, we see values of adjusted R^2 at 0.090 (1^{st} condition) and 0.065 (2^{nd} condition). When calculation is repeated for operative temperature $t_o > 29$°C we find adjusted R^2 equals 0.200 and 0.207 respectively. This supports the thesis that sensitivity to humidity increases with higher temperatures.

Table 1. Adjusted coefficients of determination (R^2) for polynomial regression (2nd degree) on Humidity Sensation Vote (HSV), separated by analytical method and test condition

	Single votes		Averaged votes	
	1st condition	2nd condition	1st condition	2nd condition
Relative humidity	0.101	0.107	0.452	0.278
Dew point	0.156	0.225	0.837	0.927
Enthalpy	0.153	0.235	0.825	0.986
Humidity ratio	0.157	0.230	0.837	0.946

Concerning the Thermal Sensation Vote (TSV) the main influencing variable is the operative temperature; the impact of humidity is well-known. It was tested, which of the above measures improves a linear regression model significantly. Table 2 shows that the dew point has lowest significance overall. At the votes of first condition RH, enthalpy and HR lie in the same range, RH falling back slightly. At the second condition enthalpy and HR influence the model more significantly than RH.

Table 2. ANOVA significance level "Pr" of improving the model for TSV prediction based on t_o through different criteria of humidity

	Single votes		Averaged votes	
	1st condition	2nd condition	1st condition	2nd condition
Relative humidity	0.00049	0.00042	0.00545	0.02053
Dew point	0.00101	0.00081	0.00712	0.02775
Enthalpy	0.00039	0.00025	0.00586	0.01607
Humidity ratio	0.00043	0.00024	0.00570	0.01566

The coefficient of determination for predicting Thermal Acceptance Vote (TAV) by operative temperature is lower as for TSV: adjusted R^2 is 0.856 (0.883 for the second condition). Again it was tested which measure of humidity improves significantly the prediction of TAV (Table 3). In this case, enthalpy and humidity ratio are within the same range and have a larger impact than relative humidity and dew point.

Table 3. ANOVA significance level "Pr" of improving the model for TAV prediction based on t_o through different criteria of humidity

	Single votes		Averaged votes	
	1st condition	2nd condition	1st condition	2nd condition
Relative humidity	0.00218	0.00159	0.08219	0.07264
Dew point	0.00246	0.00272	0.08021	0.08276
Enthalpy	0.00128	0.00103	0.06432	0.06281
Humidity ratio	0.00135	0.00103	0.06424	0.06177

In summary of the above analysis it can be stated that humidity ratio has proved to be one of the better measures (together with the enthalpy of the air) to derive the impact of combined temperature and humidity on human sensation. Therefore and as it is the measure used in the standards, the following analysis focuses on using HR for predicting the percentage of thermal acceptability.

3.2. Thermal acceptability

Thermal acceptability is here expressed by a percentage of a group of people accepting the condition of temperature and humidity, which they had been exposed to. For defining such groups two different approaches of clustering were chosen (Table 4). At first (method "C1") it was pretended the subjects did not experience another condition in the second office, so that all votes of the first condition were divided into nine groups according to the nine conditions (cf. 2.2). At second (method "C2") 28 votes closest to each of the nine defined conditions (not regarding if it was the first or second test for the subject, but excluding a second vote of the same subject) were chosen to define each group. Figure 2 shows the percentage distribution of the selected options. Linear regression models based on t_o and HR were then examined to predict the percentage.

Table 4. Mean value and standard deviation for the nine conditions, clustered according to method C1 and C2

	C1			C2		
Condition	**t_o [°C]**	**RH [%]**	**HR [g/kg]**	**t_o [°C]**	**RH [%]**	**HR [g/kg]**
26/50	26,1 (0,3)	52 (1)	10,8 (0,4)	26,1 (0,1)	51 (1)	10,7 (0,2)
26/65	26,1 (0,4)	65 (3)	13,6 (0,5)	25,9 (0,1)	65 (1)	13,7 (0,2)
26/80	26,0 (0,4)	78 (2)	16,4 (0,6)	26,0 (0,2)	79 (1)	16,6 (0,3)
28/50	28,1 (0,3)	52 (2)	12,2 (0,5)	28,0 (0,1)	51 (1)	12,0 (0,3)
28/65	28,0 (0,4)	65 (1)	15,3 (0,5)	28,0 (0,2)	65 (1)	15,4 (0,4)
28/80	27,8 (0,3)	78 (2)	18,4 (0,6)	28,0 (0,2)	78 (2)	18,6 (0,5)
30/50	30,0 (0,4)	50 (2)	13,2 (0,5)	30,0 (0,1)	51 (2)	13,3 (0,4)
30/65	30,0 (0,4)	65 (3)	17,4 (0,9)	30,0 (0,1)	64 (1)	17,1 (0,3)
30/80	29,9 (0,4)	77 (2)	20,4 (0,7)	29,9 (0,2)	78 (1)	20,7 (0,3)

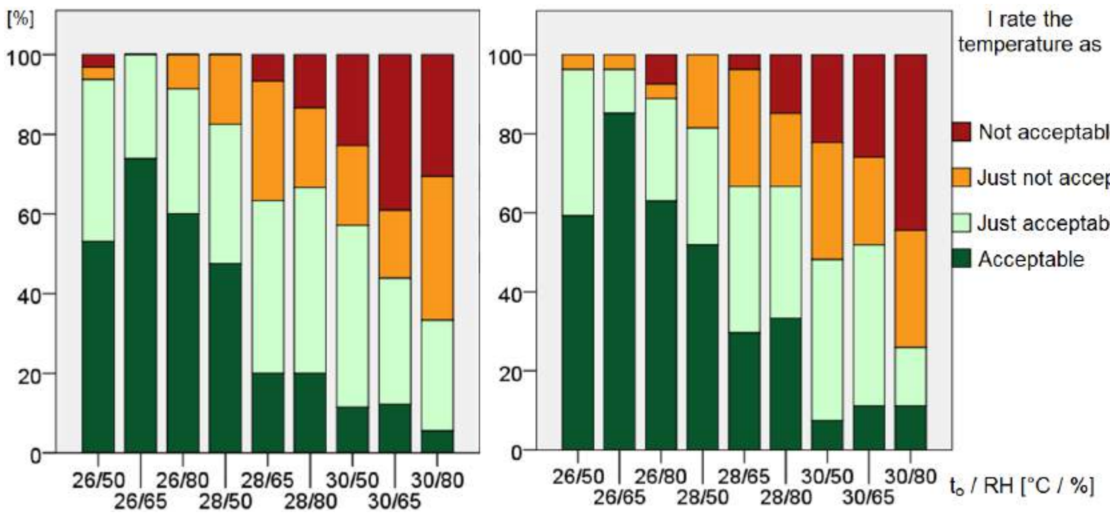


Figure 2. Responses of subjects on thermal acceptance in the nine conditions according to clustering C1 (left) and C2 (right)

As the representative measure for thermal acceptance in each group the percentage of subjects was calculated who chose "acceptable" or "just acceptable". Like presented in Table 5 this predicting model is showing a good performance. It is interesting to notice that regression of the separated votes is performing remarkably worse. Whereas the percentage of vote "acceptable" shows an adjusted R^2 of 0.787 and 0.865 respectively, the one of "just acceptable" can hardly be predicted (adj. R^2 = 0.111 and 0.092 respectively).

Table 5. Parameters of the linear regression model for predicting percentage of thermal acceptance (PTA) by operative temperature and humidity ratio, derived from clustering C1 and C2

	C1	C2
Factor t_o	-10.66	-11.06
Factor HR	-2.49	-2.39
Constant	406.43	415.29
Adjusted R^2	0.936	0.927

These models offer the chance to define a target percentage of acceptability and then receive a relationship between t_o and HR to define a maximum value of t_o by the current HR or vice versa. As in the range between 26 and 30 °C and from 10 g/kg upwards the two models are very similar, they can be summarized into one. If the desired acceptability is set to 90%, the following HR should not be exceeded dependent of the operative temperature:

$$HR < 131.53 - 4.45 * t_o \text{ [g/kg]} \qquad (1)$$

This relationship has then been compared to the relation of HR and t_o at PPD 10% (with clo=0.5, met=1.1, v_{air}=0.1 m/s) in Figure 3. Additionally the fixed limits of 11.5 and 12.0 g/kg for a maximum humidity level (cf. section 1) are shown. For an extended comfort zone, which allows higher humidity values at moderate warm temperatures, the stricter criterion was taken into account. Therefore above 26.7°C the ISO PPD method should be used, below that application of equation (1) is suggested.

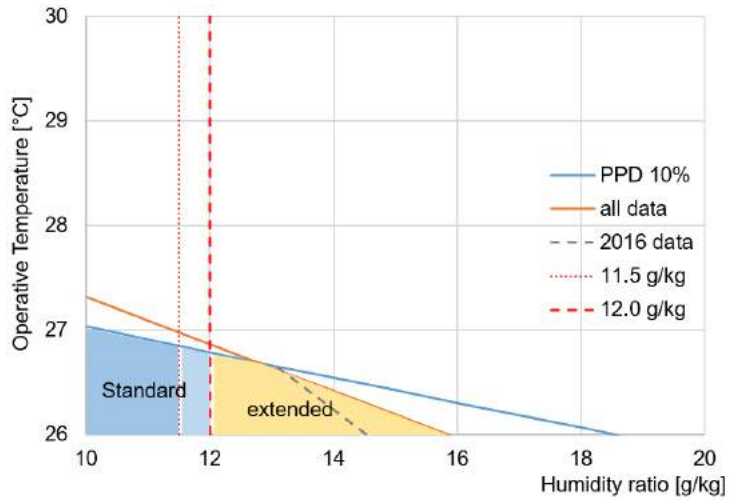


Figure 3. Extended comfort zone based on a HR/t_o relation, derived from experiments with t_o > 26°C and HR > 10 g/kg

3.3. Thermal sensation vote

It has been discussed in different publications if PMV is a good predictor for thermal sensation at elevated temperatures and humidity. The statements were not persistent. Therefore, in this section the available data is also analysed in regard to PMV. In total there are 655 votes (including the pilot tests): 327 participants with votes in first and second condition, one participant with the vote missing in first condition.

Over all votes a linear regression between TSV and calculated PMV returns an adjusted coefficient of determination of R^2_{adj} = 0.367. In average the PMV is 0.1 higher than the actual TSV. If the PMV is rounded to integer numbers, 47.8% of the predicted values match the TSV in the questionnaires ("true positive rate", TPR). Again a linear regression model based on t_o and HR is built, this time for all single votes with the person as a mixed effect to include both 60-min-votes of each participant. The true positive rate turns out to be 49.0%.

Table 6. Quality parameters of the different methods to predict actual TSV in the nine test conditions

	PMV		**Model M1**		**Model M2**	
	avg(PMV-TSV)	**TPR [%]**	**avg(M1-TSV)**	**TPR [%]**	**avg(M2-TSV)**	**TPR [%]**
26/50	0.1	60.0	-0.2	58.5	-0.1	60.0
26/65	0.4	47.1	0.1	54.0	0.1	51.8
26/80	0.0	41.1	-0.1	54.4	-0.1	44.1
28/50	0.2	48.6	0.0	48.6	0.0	46.2
28/65	0.2	41.4	0.1	40.0	0.1	46.8
28/80	0.0	38.3	0.0	38.3	0.0	37.9
30/50	0.0	47.3	-0.0	41.9	-0.1	44.8
30/65	0.0	53.8	0.1	51.6	0.0	49.4
30/80	-0.1	50.0	-0.0	51.5	0.0	51.5

It was then examined if the model could be improved by any personal factors of the participants. Tested by ANOVA, the body surface area (DuBois 1916) showed a significant improvement by 0.0006 (model "M1") and the average outdoor temperature of the four preceding weeks induced a further improvement by 0.06 (model "M2"). However, there is no improvement on the true positive rate in total, which is at 48.2%. The changes in the results were also calculated for each of the nine conditions and listed in Table 6.

Figure 4 shows the distribution of the difference between PMV and TSV for the nine conditions as a boxplot chart. The median values and boxes at 26°C (50%, 65%, 80% RH) show the PMV rather overestimating thermal sensation. At 26°C/65% RH the median is almost half a scale point above 0. At the 28°C conditions (50%, 65%, 80% RH) the medians are very close to zero, all slightly positive. At 30°C in each of the three conditions the median is below zero, so that in more than 50% of the cases PMV underestimates TSV.

When comparing the calculated difference at each RH-80%-condition to the others at the same temperature level, they seem to be always lower. However, this trend is not significant and not as obvious as it was derived from data of the 2016 experiments only (Kleber et al., 2018).

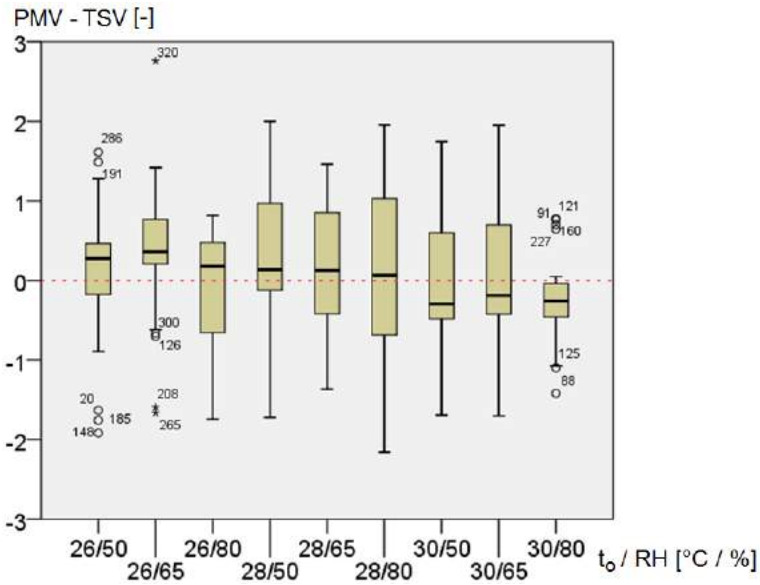


Figure 4. Difference of PMV and actual TSV in the nine conditions as boxplot chart (box marks 25, 50 and 75 percentiles; whiskers max 1.5 height of box, extreme outliers 3.0 height of box)

3.4. Comparison with other studies

Analysis in this section makes use of data from other studies and compares it to this study. The original reference values of those studies were used and data from this study was adapted. Those reference values (indices like effective temperature) were calculated by the statistical software R and the package "comf" (Schweiker, 2016).

As presented in a previous paper, results of this study have been already compared to existing evaluations (Kleber et al., 2018). A comparison with a Chinese study (Jin et al, 2017) of young people, who were born and raised in hot-humid areas of China, showed that thermal acceptability in the study at hand was much lower. Now votes of 2015 and 2017 experiments are included and displayed in Figure 5. For building the percentages here 28 votes for each of the nine conditions have been included and only one vote of each participant has been used (method "C2" excludes mixed effects here, cf. 3.2). The German participants are not adapted to warm and humid climate and they react clearly more sensitive to an increasing effective temperature than the Chinese participants do.

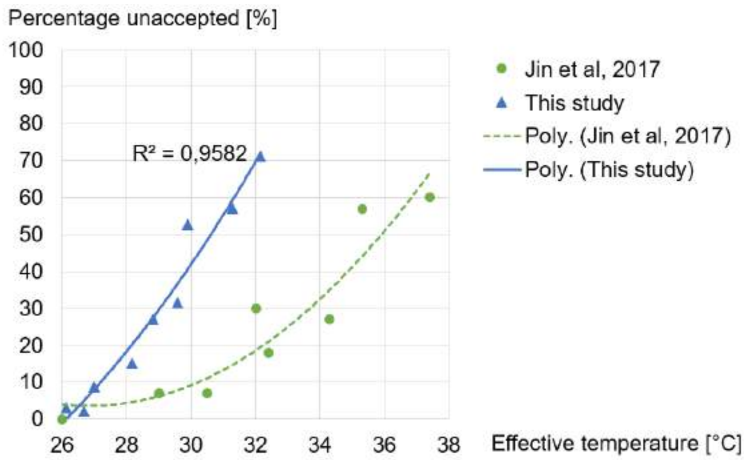


Figure 5. Comparison of percentage of acceptance in relation to effective temperature in this study and the study of (Jin et al, 2017)

Another study, conducted in the United States (Zhai, 2015), showed instead percentages of thermal acceptability very similar to the ones of this study. Including now the additional data as well, those results are confirmed (Figure 6). Again, effective temperature is displayed as the related measure on the x-axis, as it had been originally used by Zhai in his publication. In general a similar sensitivity of the participants to higher temperature and elevated humidity reveals. A slightly lower percentage below 28°C and a higher percentage above 30°C can be assumed for this study, but cannot be statistically proved. As it is not mentioned in (Zhai, 2015), it is assumed that the participants were adapted to moderate climate and therefore vote similar to the German participants.

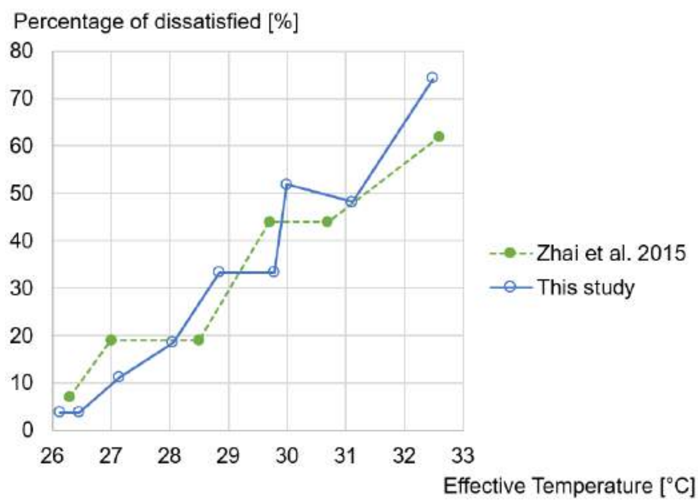


Figure 6. Comparison of percentage of dissatisfied in relation to effective temperature in this study and the study of (Zhai et al, 2015)

Additionally to updating the existing analysis above, another study was used to compare results. In (Jing et al, 2013) the responses of 20 participants to nine combinations of temperature and humidity were taken in a chamber experiment and analysed in terms of a possible negative effect of humidity on thermal comfort. The humidity sensation vote (HSV) was questioned by an identical scale (7-point from “very dry” to “very humid”), but with partly different humidity levels (Figure 7). It has to be regarded that the clo value is 0.3, whereas the average clo in this study was 0.5. It is also important, that the relative humidity in the first conditions was 10% lower and in the second conditions 5% lower at the Chinese experiment.

Up to 65% RH the votes are in a similar range around "neutral" beside the one at 30°C in this study: at 30°C and 65% RH the average vote is higher than "slightly humid". With 80% RH all thermal sensation is clearly higher at 26°C and 28°C and increases by more than 1 scale point with 30°C. Those findings match with other studies, which stated that humidity could be sensed by the participants only at higher levels of temperature and/or humidity. The votes at the 80% RH level are very similar in both studies in spite of the different clo values.

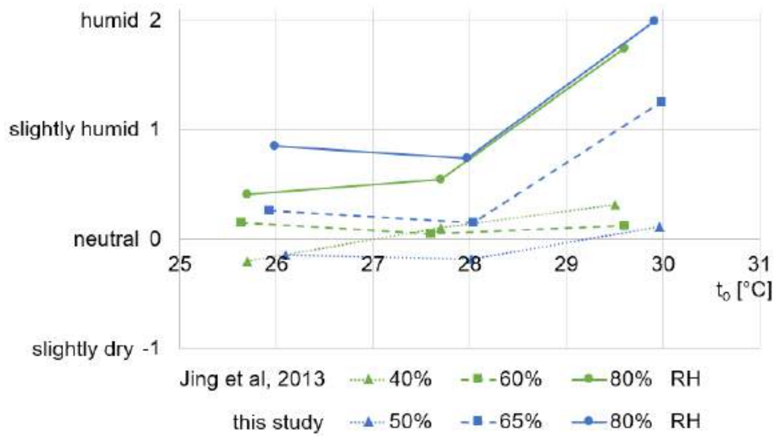


Figure 7. Comparison of humidity sensation (HSV) in relation to operative temperature in this study and the study of (Jing et al, 2013)

Regarding thermal responses, Jing et al also had questions on thermal acceptance (3-point-scale from ASHRAE) and on comfort (TCV, 4-point-scale) in their questionnaire, but unfortunately the scales were very different from the ones in this study. Therefore only TSV could be compared. Figure 8 shows the average votes in the nine conditions of each study. In spite of the different clo level and partly different RH level, at the 26°C and 28°C conditions the votes were close to one another in each study, not differing much by the relative humidity level. At the 30°C level a large spread can be recognized in the votes of the Jing 2013 study. The vote at 29.6°C and 80% RH is higher than in this study at a similar condition, even though the clo value is lower. In this study the spread between the 50% RH and 80% RH sensation at 30°C is in a similar range like at 26°C or 28°C.

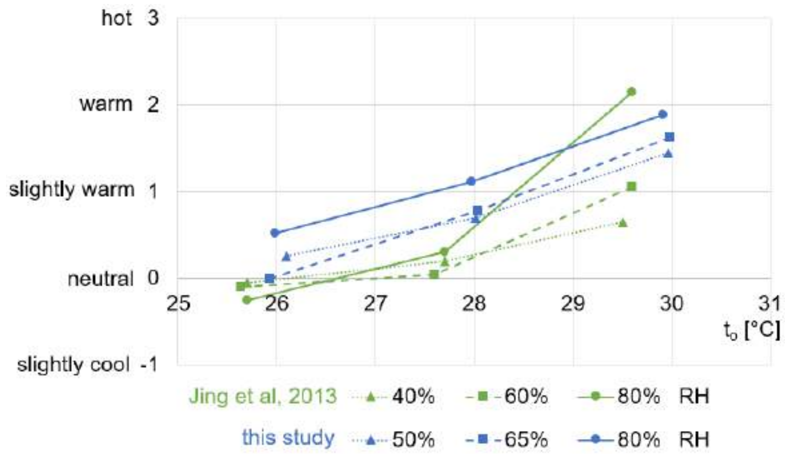


Figure 8. Comparison of thermal sensation vote (TSV) in relation to operative temperature in this study and the study of (Jing et al, 2013)

4. Discussion

Analysis has shown interesting findings regarding comfort at warm and humid conditions. However, there are different aspects, which have to be critically discussed. The described extended comfort zone is a reasonable antithesis to a fixed upper humidity limit of e.g. 11.5 g/kg, but it refers in the end only to a small range of temperature and humidity. Due to the experimental setup the validity covers only temperatures above 26°C (and up to 30°C). It could be shown that in this range a linear model is providing good results. But it is an important question, what would happen at conditions where t_o is lower than 26°C and HR is higher than 12 g/kg.

The goal of this study was to examine comfort criteria at warm and humid conditions in general, but the adapted criteria were then applied for rating comfort at residential buildings. It has to be discussed if the experimental design can be improved in the future. This concerns the length of the experiment on the one hand and the spatial setup on the other.

Regarding the duration of the experiments, literature review showed that in warm-humid or hot-humid experiments exposure times from 20 minutes (Fang et al, 1998) across 60 minutes (Fountain et al, 1999) (Jin et al 2017) and 120 minutes (Toftum et al, 1998) up to 180 (Tsutsumi et al, 2007) minutes have been applied. It can be concluded that after 60 minutes only small changes occurred in the sensation and perception votes of the participants, whereas especially within the first 30 minutes the changes were larger. However, when looking at residential comfort, the exposure to conditions outside the comfort range can be clearly longer and be affected by alternating situations (e.g. day and night, action and resting). A test facility like LOBSTER offers controllability and good opportunities to measure the relevant parameters, but daily routine of a residential can hardly be reproduced. On the contrary, in a field study it will be difficult to record the responses of the participants and the necessary parameters. In this context one main question will be how adaptation and exhaustion (especially of older residents) during longer exposures (e.g. heat waves or sultry weather periods) will impact on thermal comfort and to which extent they might compensate each other.

Concerning the spatial setup, in this study the subjects were asked to sit at the desk of that particular test room and fill the questionnaires at the computer. This situation matches well with office work in a non-residential building, but does not depict behaviour in a residential space. In an apartment the resident can choose his position within the room (sitting on a chair, standing, sitting on the couch, lying on the bed etc.), he can go to another room (different temperature, orientation, furniture, materials etc.) or even leave the building. As most comfort research laboratories have more than one room, the imitation of a residential space could be possible to some extent. Living labs in the field of smart home exist and enable research during consecutive days or weeks. For example the “Well living lab” in Rochester, USA (Jamrozik et al, 2018), provides conditioned spaces for comfort research, which can be equipped as residential modules. Future research should also investigate warm and humid indoor climate in a setup like this to learn more about its long-time influence.

5. Conclusions

In this study comfort criteria of persons who have been living in the Karlsruhe region for at least two years and who are adapted to the current climate conditions (temperate climate) have been analysed at warm-humid conditions. With more than 300 participants a large sample could be reached and general questions on humidity measures and limits of comfort were examined. Comparison to the PMV model and to similar studies was performed. The key findings are:

- Humidity ratio HR was proved to be a better measure than relative humidity or dew point to represent the influence of humidity on humidity sensation (HSV), thermal sensation (TSV) and thermal acceptance (TAV)
- Using the air's enthalpy as a predictor lead to similar performance of the applied regression models like humidity ratio.
- As the impact of air humidity on comfort is strongly dependent on the room (operative) temperature, an upper humidity limit for summer conditions should be at least defined in combination with temperature.
- Within the defined experimental conditions the percentage of acceptability could be described by a simple linear regression model based on t_o and HR. By this model acceptability can be calculated through a simple formula, yet more precisely than only by HR and in the same range as through PPD.
- Within the applied range of humidity and temperature a linear regression model for predicting TSV based on t_o and HR performed slightly better than PMV.
- This model could be significantly improved by including body surface area or the four-week-average of outdoor temperature, but tests of true positive rate did not reveal a relevant difference.
- Based on the acceptability model, for this climate region an extended comfort zone at summer conditions was suggested; in contrast to a strictly limited humidity ratio.
- Responses of subjects not adapted to warm-humid conditions showed a slight overestimation of TSV by PMV at 26°C, which changes to a small underestimation at 30°C; humidity did have no influence on the prediction quality of PMV.
- The comparison of thermal acceptance from this study with a similar study at a warmer and more humid climate region showed that ethnic origin and long-term adaptation played a role in the perception of warm-humid indoor conditions; other studies with comparable preconditions showed responses similar to the ones in this study.

Comparisons with other studies have been only performed on the published and processed data. It would be of advantage to cooperate with other researchers and combine raw data of similar experiments to increase sample size and validity. Analysis of the available data in this study will continue in 2018 and further results are going to be published.

Acknowledgements

This work was enabled within the project "raum/klima/putz", which is financed by the German federal state foundation "Baden-Württemberg Stiftung".

References

Djamila, H.; Chu, C.-M., Kumaresan, S., 2013. *Field study of thermal comfort in residential buildings in the equatorial hot-humid climate of Malaysia,* Building and Environment (62), pp. 133-142

Dubois, D., Dubois, EF., 1916. *Clinical calorimetry: a formula to estimate the approximate surface area if height and weight be known*, Arch Int Med 17, pp. 863-71

Fang, L., Clausen, G., Fanger, P.O., 1998. *Impact of Temperature and Humidity on the Perception of Indoor Air Quality*; Indoor Air 2, Vol. 8; pp. 80-90

Fanger, P.O.; *Thermal Comfort*; Danish Technical Press, 1970

Feriadi, Henry; Wong, Nyuk Hien, 2004. *Thermal comfort for naturally ventilated houses in Indonesia*, Energy and Buildings 7, pp. 614-626

Fountain, M.E., Arens, E.A., Xu, T., Bauman, F.S. and Oguru, M., 1999. *An Investigation of Thermal Comfort at High Humidities*. In: ASHRAE Transactions 105(2)

Jamrozik, A., Ramos, C.; Zhao, J.; Bernau, J.; Clements, N.; Wolf, T.V.; Bauer, B., 2018. *A novel methodology to realistically monitor office occupant reactions and environmental conditions using a living lab*, Building and Environment

Jin L., Zhang Y., Zhang, Z., 2017. *Human responses to high humidity in elevated temperatures for people in hot-humid climates*; Building and Environment, 114 (2017), pp. 257–266

Jing, S., Li, B., Tan, M., Liu, H., 2013. *Impact of Relative Humidity on Thermal Comfort in a Warm Environment*, Indoor and Built Environment 4, Vol. 22, pp. 598-607

Kitagawa, K., Komoda, N., Hayano, H., Tanabe, S., 1999. *Effect of humidity and small air movement on thermal comfort under a radiant cooling ceiling by subjective experiments*; Energy and Buildings 2, Vol. 30, pp. 185-193

Kleber, M., Wagner, A., 2018. *Investigation of indoor thermal comfort in warm-humid conditions at a German climate test facility.* Building and Environment

Mehnert, P.; Malchaire, J.; Kampmann, B.; Piette, A.; Griefahn, B.; Gebhardt, H., 2000. *Prediction of the average skin temperature in warm and hot environments*; European journal of applied physiology, 82, pp. 52-60

Schweiker, M. “comf” package; https://cran.r-project.org/package=comf

Shi, Xinli; Zhu, Neng; Zheng, Guozhong, 2013. *The combined effect of temperature, relative humidity and work intensity on human strain in hot and humid,* Building and Environment (69), pp. 72-80

Toftum, J., Jorgensen, A., Fanger, P.O, 1998. *Upper limits of air humidity for preventing warm respiratory discomfort*; Energy and Buildings 1, Vol. 28, pp. 15-23

Tsutsumi, H., Tanabe, S., Harigaya, J., Iguchi, Y., Nakamura, G., 2007. *Effect of humidity on human comfort and productivity after step changes from warm and humid environment*; Building and Environment 12, Vol. 42, pp. 4034-4042

Wagner, A. et al, 2018. *Exploring Occupant Behavior in Buildings,* Chapter 7.2.4, pp. 178. Cham: Springer International Publishing AG

Zhai, Y., Zhang, Y., Zhang, H.; Pasut, W., Arens, E., and Meng, Q., 2015; *Human comfort and perceived air quality in warm and humid environments with ceiling fans*. Building and Environment 90; pp 178-185

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Comfort, climatic background and adaptation time: first insights from a post-occupancy evaluation in multicultural workplaces

Luisa Pastore[1] and Marilyne Andersen[1]

[1] Laboratory of Integrated Performance In Design (LIPID), School of Architecture, Civil and Environmental Engineering (ENAC), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland, luisa.pastore@epfl.ch

Abstract: One of the effects of globalization and work mobility is the increasing multiculturalism in the workplace. While contemporary design policies for energy efficiency and comfort regulations are moving towards the adoption of models customized for local communities, consideration on the co-existence of people with different origins is underestimated in the current comfort debate. The aim of this study is to show whether building occupants' comfort rating can be affected by their climatic background as well as their duration of living in the current country of residence. A post-occupancy evaluation (POE) was carried out in two office buildings located in Switzerland accounting for a high rate of international employees. Questionnaires were distributed among the building occupants with the aim to investigate, among other things, their satisfaction with temperature, air quality, lighting, noise, view to the outside and privacy. With regard to thermal comfort and air quality, the results show that indeed people's rating varied significantly according to their climate of origin as well as with the time span spent in the country. However, no statistically significant differences were found in terms of their satisfaction level with the other above-mentioned comfort factors. Overall, the study provides new insights on the relationship between comfort perception, cultural background and people's adaptive behavior, raising questions about the appropriateness of current comfort models and design strategies to achieve adequate environmental conditions in workplaces.

Keywords: Post-occupancy evaluation, climate, thermal comfort, air quality, adaptive comfort

1. Introduction

In a world increasingly interconnected as a result of massive and fast spread of information, people and goods, our cities are becoming more and more international. In the last couple of decades, labour force mobility – both between jobs and within and between countries – has been promoted at the communitarian and international levels to contribute to «…economic and social progress, a high level of employment, and to balanced and sustainable development…» (EU Commission, 2012). This is resulting in an increasing creation of work environments characterized by a progressive integration of locals with people coming from different countries, carrying with them habits and the culture of their places of origin. This includes also their own notion of comfort, in its many aspects.

Nevertheless, as the Society for Human Resource Management stated «…even though organizations move beyond their borders and reach into other territories, not all employees are immediately "global people"…» (SHRM, 2015), underlying by this the importance for these people to incorporate and get used to new social, cultural and environmental habits in their workplace. For many years, research on human comfort has raised awareness on the importance of extending the comfort debate from physiological to also psychological and behavioral aspects (Cole et al, 2008). An outcome of this more comprehensive approach has been, for example, the consideration of human ability to adapt to the local indoor and outdoor thermal environment, which became essential for the development of the adaptive thermal model now included in ASHRAE and European standards (de Dear and Brager, 1998; Nicol et al. 2012).

In contemporary energy and architectural design and policy, however, while an increasing awareness is raising for the adoption of climate-specific comfort models and strategies, the simultaneous presence of people with different geographic backgrounds, that occurs for example in multicultural work spaces, is almost entirely neglected.

The aim of the study presented in this paper is to broaden our understanding of the influence of people's climatic background and adaptation time to new environments to their comfort perception in workplaces. The investigation is carried out through field studies conducted in Switzerland, which is representative of international work environments. The country has indeed one of the highest proportions of foreigners among all nations (24.6% in 2015), including cities like Geneva or Lausanne that have, respectively, around 48% and 41% of the permanent population coming from abroad (Swiss Federal Statistical Office, 2017).

2. Method

Data discussed in this paper originate from an extensive post-occupancy evaluation (POE) conducted by the authors in some office buildings located in Switzerland. The POE included seasonal environmental monitoring campaigns (long term and instantaneous measurements), seasonal point-in-time comfort surveys (associated with the instantaneous measurements) and seasonal long-term comfort surveys. Only data resulting from the latter are analysed and commented in this paper.

2.1. Long term survey

Buildings' occupants who agreed to participate in the research had to fill a preliminary background questionnaire to provide some personal information such as age, gender, work type, working hours per week, country of origin and duration of their living in Switzerland.

An extensive on-line survey was sent to the buildings' occupants twice during the year 2017: the first time at the end of winter (March-April 2017) and the second time at the end of summer (September 2017). The aim of the questionnaire was to investigate, among other things, the level of satisfaction they had experienced during the two seasons with regard to comfort overall, indoor environmental quality (IEQ) factors (temperature, light, air quality and noise), view to the outside and privacy. Ratings were registered through a 7-point Likert scale, with 1 corresponding to "Very dissatisfied" and 7 to "Very satisfied". Open questions to allow participant to add their own comments were also included in the questionnaire.

2.2. Description of the case studies and of the population

For this study, data coming from two case studies were taken into account; the first (CS1) is located in Lausanne and the second (CS2) in Geneva.

They both obtained the Minergie certification, a label attesting the high-energy efficiency of new or refurbished buildings in Switzerland. This certification system relates primarily to the annual energy used by the building for heating, hot water and electrical ventilation, requiring in most cases airtight building envelopes and the use of an energy-efficient ventilation system.

The selected buildings are equipped with HVAC systems and have fixed glazing in their facades. However, every office in CS1 is provided with hopper-type opaque elements that can be manually operated to allow for natural ventilation.

The buildings were both occupied in 2015 to host prevalently research and academic personnel and are characterized by a significant foreign population. Fig. 1 describes the demographics of the two case studies: 60 answers were collected from CS1 and 130 from CS2; respondents were from 17 different nationalities in CS1 and from 23 different nationalities in CS2, entailing the 75% and 56% of answers from non-Swiss employees respectively.

In both buildings, the majority of respondents have lived in Switzerland for more than 5 years, followed by a smaller percentage of people who have lived in the country for the last 2-5 years and a further reduced amount of people who have moved to the country less than 1 or 2 years before the research took place.

Based on an updated Köppen–Geiger climate classification (Peel et al., 2007), building users were grouped in 3 categories depending on their country of origin:

- Hot-summer Mediterranean climate (M): includes those countries generally lying between the tropics and the polar regions, characterized by hot to mild temperatures all year round (average temperature above 22°C in the warmest month and between 0° and 18°C in the coldest).
- Temperate Oceanic and Continental climate (OC): includes those countries characterized by cold winters (average temperature ≤ 0°C) and mild (temperate oceanic) to hot (continental) summers.
- Tropical and Humid Subtropical climate (TS): includes those countries typically lying at tropical and subtropical latitudes (generally between latitudes 35 north and south of the Equator), characterised by warm to hot summers and mild (subtropical) to warm (tropical) winters.

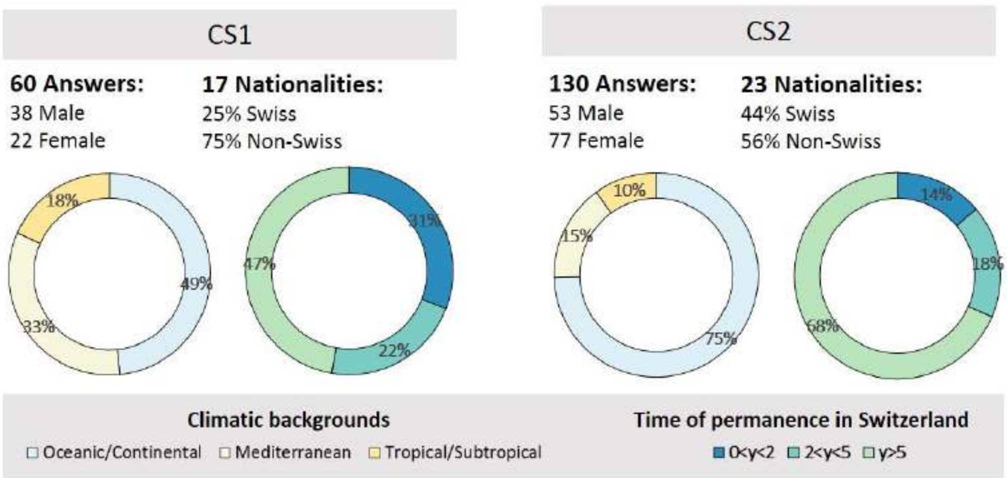


Figure 1. Demographics of the two case studies

2.3. Data analysis workflow and statistical methods

Preliminary analyses of the IEQ ratings showed great differences between the occupants' satisfaction levels in CS1 and in CS2: they revealed, on average, positive votes in CS1 – though with a considerable percentage of dissatisfied occupants in terms of temperature ratings (48%) –, while a high rate of dissatisfaction was observed in CS2, in particular with regard to temperature and air quality (always >50% of negative votes).

This initial observation raised the question whether the building design *per se* could play a main effect in the votes of the occupants and whether, as a consequence, data from each building had to be assessed individually. A multifactor analysis of variance (ANOVA) was conducted towards this end and confirmed the prevalent effect of the building on all the considered comfort factors, leading to the decision of analysing the datasets of CS1 and CS2 separately. The multifactor ANOVA also revealed a significant effect of gender and office orientation on the comfort responses. Further multifactor ANOVA tests excluded however the interaction of these two factors with the independent variables under consideration in this study, i.e. climate and time spent in the country.

Shapiro-Wilk tests and Q-Q plots revealed non-normal data distributions for both buildings, entailing the application of non-parametric testing for statistical analysis. Kruskal-Wallis test was used to assess the statistical significance (NHST, Null Hypothesis Significance Testing) of the difference in people's satisfaction votes based on their climatic background (OC, M and TS); and their duration of living in Switzerland (0-2y, 2-5y, >5y).

When a significant effect was found, a post-hoc test using Mann-Whitney test with Bonferroni correction was applied to check the statistical significance of the difference between pairs of groups. For both Kruskal-Wallis and Mann-Whitney tests, results were declared statistically significant when the probability that a difference could have arisen by chance was below 5% ($p \leq 0.05$). To infer whether the differences detected have any practical relevance, the effect size was also estimated through the formula: $r=z/\sqrt{N}$, where N is the total number of samples (Fritz et al. 2011). In interpreting the outcomes, benchmarks (in absolute values) were used to indicate small ($0.1 < r <= 0.3$), medium ($0.3 < r <= 0.5$) versus large ($r > 0.5$) effects. Statistical tests were performed with the *R software.*

3. Results

3.1. Influence of the climate of origin

Table 1 provides the descriptive statistics from the analysis of the long-term questionnaires based on the climatic backgrounds of the buildings' occupants. For each investigated comfort factor, the table presents the means and the medians of the occupants' satisfaction votes in the three climate groups and the interpretation of their statistical significance (p).

Table 1. Summary of comfort factor scores (means and medians) based on the climatic background and statistical significance of the difference between the groups

	CS1				**CS2**			
	OC **M│Mdn**	M **M│Mdn**	TS **M│Mdn**	*p*	OC **M│Mdn**	M **M│Mdn**	TS **M│Mdn**	*p*
Ov. Comfort	5.04│6.00	5.44│6.00	5.75│6.00	n.s.	3.92│4.00	3.95│4.00	3.80│4.00	n.s.
Temperature	**3.96│3.50**	4.78│5.00	**5.75│6.00**	**0.03***	3.48│3.00	3.32│3.00	3.07│3.00	n.s.
Air quality	5.18│5.50	5.67│6.00	5.75│6.00	n.s.	**3.20│3.00**	3.37│3.00	**4.27│4.00**	**0.05***
Lighting	4.93│5.00	4.61│5.00	5.25│5.50	n.s.	3.91│4.00	3.70│3.50	4.80│6.00	n.s.
Acoustics	4.86│5.00	5.11│6.00	6.00│6.00	n.s.	4.74│5.00	5.00│5.00	5.20│5.00	n.s.
View out	5.46│6.00	5.83│7.00	5.92│6.00	n.s.	4.05│4.00	4.21│5.00	4.60│5.00	n.s.
Privacy	4.57│4.00	5.33│6.00	5.50│6.00	n.s.	4.04│4.00	3.50│3.50	4.13│4.00	n.s.

***p<0.001; **p<0.01; *p<0.05; n.s. = not significant
Values in bold are those of the pairs resulting significantly different in the Mann-Whitney test

In CS1, the NHST test revealed a significant effect of the climate of origin on temperature ratings ($p = 0.02$). A post-hoc test using Mann-Whitney tests with Bonferroni correction showed, in particular, the significant differences between the groups OC and TS ($p = 0.03$), with effect size of practical relevance ($r = -0.40$).

In both seasons, scores attributed by occupants from Oceanic/Continental climate were, on average, never above the satisfaction threshold, while respondents from Mediterranean and Tropical/Subtropical climates rated the temperature more positively.

More precisely, on average the OC group found the temperature in their office "somewhat cold" (leaning towards "neutral") in the winter and "cold" (leaning towards "very cold") in the summer. The thermal conditions were described instead by the majority of people from M and TS groups as "neutral" for both seasons, with answers from M leaned slightly towards "somewhat cold" in winter and answers from TS lean slightly towards "somewhat hot" in summer.

No significant difference between climate groups was detected with regard to the other IEQ factors nor with view to the outside and privacy. However, a clear trend can be recognized between the groups: occupants with Tropical/Subtropical climatic background expressed on average always a higher satisfaction for all the comfort factors, followed in sequence by participants from Mediterranean and Ocenic/Continental climates (except for lighting, which is rated slightly lower by M than by OC).

These variations in ratings of CS1 are more clearly depicted by the radar chart of Fig. 2 (left), where the areas defined by each climate groups can be interpreted as their grade of tolerance toward the working environment.

A lower performance of CS2 led to generally poorer mean comfort votes for all groups in this building. No statistically significant effect of the climatic background was found on comfort ratings in this case, except for air quality in the Mann-Whitney pairwise comparisons between OC and TS ($p=0.05$, $r=-0.22$). From the comfort profile in Fig. 2 (right), however, TS showed again a higher level of satisfaction for all factors, except temperature and overall comfort whose rating was more or less equivalent to the other groups and on average always below the satisfaction threshold.

To sum up, this analysis showed that the rating of temperature in CS1 and of air quality in CS2 were significantly influenced by the climate of origin of the building occupants, and that people from the Tropics and Subtropics were generally more tolerant towards the indoor environment than people from colder countries. (Fig. 3).

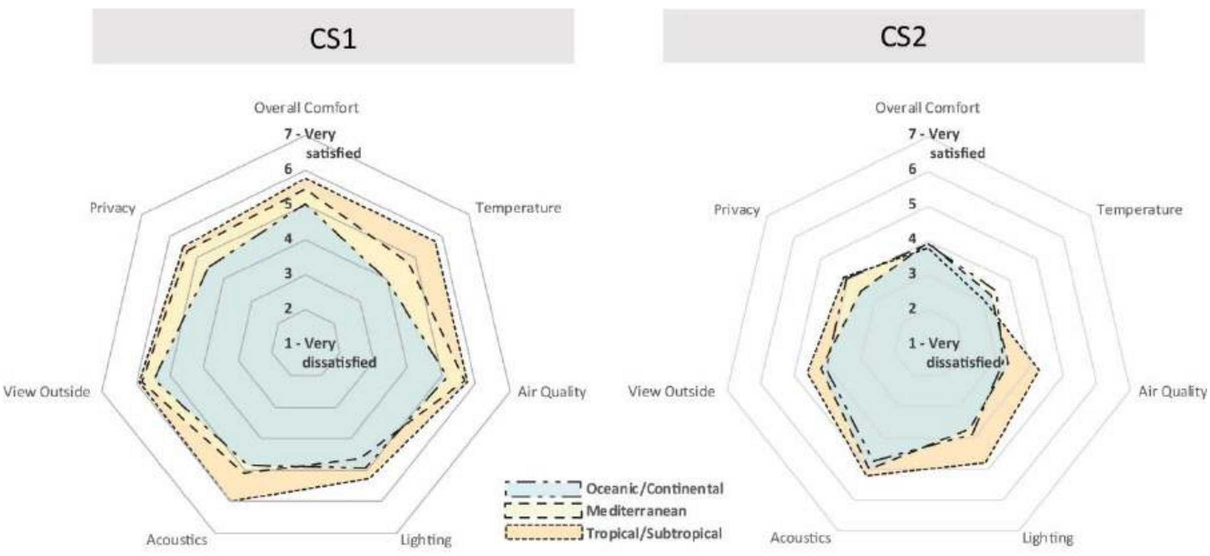


Figure 2. Comfort rating profiles based on climate of origin in CS1 (left) and in CS2 (right)

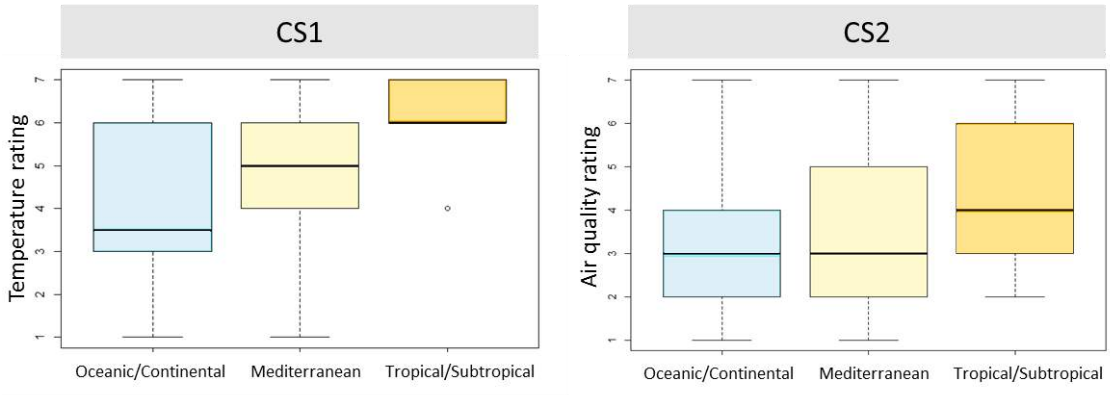


Figure 3. Rating distributions for temperature in CS1 (left) and air quality in CS2 (right) based on climate of origin (1 corresponds to “Very dissatisfied” and 7 to “Very satisfied”)

3.2. Influence of the duration of residence in the country

As shown in Table 2, the score for temperature in CS1 and for air quality in CS2 were found to be affected also by how long the occupants have been living in Switzerland. More precisely, significance testing revealed differences between the groups “0-2y” and “>5y” in temperature ratings (p=0.05, r=0.35), with thermal comfort attaining very positive score in CS1 during the first two years of living in the country, while it moves towards a neutral opinion over time (Fig. 5).

In CS2, the NHST test showed a significant effect of duration of residence in the country on air quality (p = 0.02). A post-hoc test confirmed, also in this case, the significant differences between the groups “0-2y” and “>5y” (p = 0.02, r=0.26). In particular, air quality was rated positively by the majority of occupants having moved recently to Switzerland while it became more and more dissatisfying as the duration of the stay increased.

42% of dissatisfied votes recorded in the winter and 58% in the summer attributed the reason of their discomfort to “air too stuffy”. Other reasons invoked were “air too smelly” (28% in the winter and 23% in the summer) and “air too dry” (28% in the winter and 19% in the summer). As the point-in-time measurements taken during the POE revealed CO_2 concentrations in the air always within acceptable limits, one may associate discomfort votes to psychological rather than physiological reasons. It could be argued, however, that the time spent in the building rather than the duration of residence in the country could also be the cause for the increasing rate of dissatisfaction in this case. Nevertheless, descriptive statistics showed that people who had started to work in the building for less than 6 months were actually the least satisfied with air quality. Significance tests confirmed in any case that there was no relationship between satisfaction with air quality and the time spent in the building.

To summarize, this analysis demonstrated that the rating of temperature in CS1 and of air quality in CS2 were significantly influenced not only by climatic background but also by the time spent in the country, and that people’s opinion for these factors tended to become more negative over time (Fig. 5). With regard to the other aspects of comfort, for occupants who spent less than 2 years in Switzerland the mean votes of satisfaction were in most of the cases very close to the rest of the respondents’ votes, although generally slightly more positive (Fig. 4).

Table 2. Summary of comfort factor scores (mean and standard deviation) based on duration of residence in Switzerland and statistical significance of the difference between the groups

	CS1				CS2			
	0-2y **M|Mdn**	2-5y **M|Mdn**	>5y **M|Mdn**	*p*	0-2y **M|Mdn**	2-5y **M|Mdn**	>5y **M|Mdn**	*p*
Ov. Comfort	5.56|6.00	5.42|6.00	5.04|6.00	n.s.	4.11|4.00	3.96|4.00	3.85|4.00	n.s.
Temperature	**5.38|6.00**	4.83|5.00	**3.80|4.00**	**0.05***	3.56|3.50	2.77|2.50	3.54|3.00	n.s.
Air quality	5.63|6.00	5.92|6.00	5.28|6.00	n.s.	**4.39|4.50**	3.45|3.00	**3.11|3.00**	**0.02***
Lighting	5.00|5.00	4.25|4.50	5.12|5.00	n.s.	4.06|5.00	4.13|4.00	3.92|4.00	n.s.
Acoustics	5.00|5.50	5.25|6.00	5.20|6.00	n.s.	4.72|5.00	4.96|5.00	4.82|5.00	n.s.
View out	5.44|6.00	5.83|7.00	5.60|7.00	n.s.	4.22|4.50	4.14|5.00	4.12|4.00	n.s.
Privacy	5.38|6.00	5.33|6.00	4.72|4.00	n.s.	3.94|4.00	3.30|3.00	4.15|4.00	n.s.

***p<0.001; **p<0.01; *p<0.05; n.s. = not significant
Values in bold are those of the pairs resulting significantly different in the Mann-Whitney test

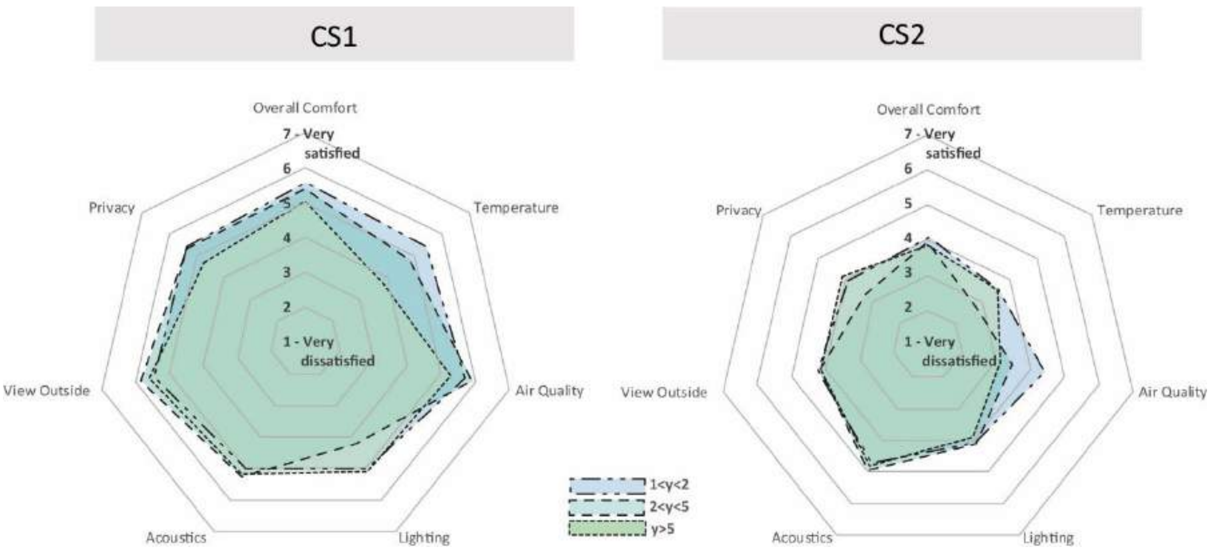


Figure 4. Comfort rating profiles based on duration of residence in Switzerland in CS1 (left) and in CS2 (right)

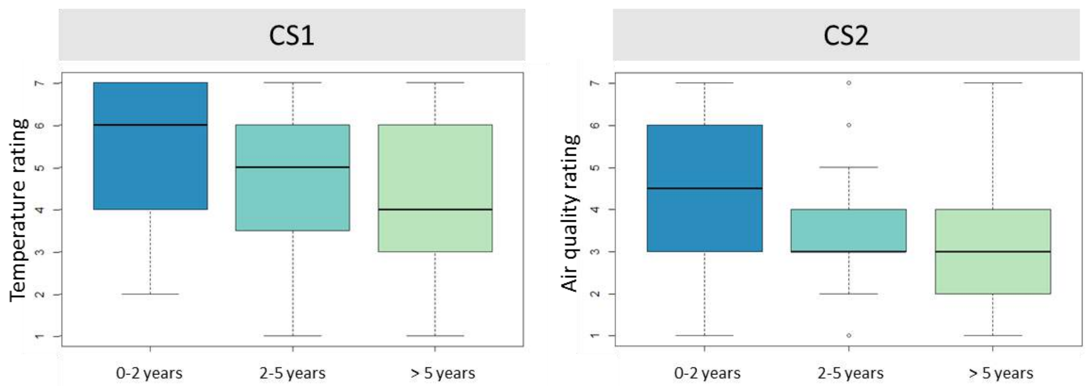


Figure 5. Rating distributions for temperature in CS1 (left) and air quality in CS2 (right) based on duration of residence in Switzerland (1 corresponds to “Very dissatisfied” and 7 to “Very satisfied”)

4. Discussion

Among all the considered comfort factors, the satisfaction with temperature and with air quality were found to be significantly influenced by the climatic background of the building users, as well as the duration of their residence in the country. The climate of origin and the time spent in Switzerland were found to be dependent variables (p-value < 0.05 in Chi-Squared test) although no interaction of the two was found in the comfort factors rating.

With regard to temperature, comparing the results between CS1 and CS2, it emerges that the influence of climatic background and of the duration of residence in the country is not substantial when the building performs very poorly (>55% of dissatisfied). On the contrary, they appear to produce an effect when the building thermal performance becomes more acceptable (67%(±5%) of satisfied and neutral opinions).

With regard to air quality, satisfaction doesn't vary significantly with the climate of origin or the duration of residence in Switzerland in CS1 where it is rated positively by over 70% of respondents, but it does in CS2 where 58%(±3%) of respondent were not satisfied.

From this particular study it emerged, therefore, that if the building performs very poorly there is no observable effect of climatic background or time of residence in Switzerland on satisfaction with temperature, but there is for air quality. On the contrary, if the building performs generally well, an influence of the climate of origin and duration of permanence in the country becomes evident on temperature ratings but not on air quality votes. To what extent the building performance plays a role in detecting a difference in comfort rating is however difficult to establish.

On the other hand, the study shows that people from Tropical/Subtropical and Mediterranean climates generally tend to be more tolerant towards indoor environmental factors than people from Oceanic/Mild summer continental climates. In particular, a significant difference between OC and TS was found for temperature ratings in CS1, showing that employees from warmer regions were comfortable in lower ranges of temperature than occupants from colder countries. This may be explained by the fact that people from the Tropics and the Subtropics are generally more accustomed to work in air-conditioned buildings with little to no mechanical heating operating in the coldest days of the year. This hypothesis would in fact be consistent with results from a test room experiment conducted by Kalmár (2016) where he observed that people with warmer thermal background preferred lower temperatures than people from a colder country. In spite of this fact, he found that after 1.5 hours exposure to a very warm environment (30°C), subjects from colder regions felt "slightly warm" or warmer while those from warmer regions tend to rate their thermal sensation as neutral, showing a generally more tolerant attitude. Reactions to very warm environments were not possible to observe in our case, because of air-conditioning use.

Moreover, these findings are actually also aligned with a study that explored outdoor thermal comfort perception in urban public places of multicultural cities showing significant differences in terms of thermal sensation votes' depending on cultural and climatic backgrounds of the interviewees (Kenawy and Elkadi, 2013).

Another aspect that is worth to mention is that, irrespective of climate groups, all median votes for temperature were more positive in the winter than in the summer. This could reveal the inappropriate design and application of air conditioning and mechanical ventilation over personal control and passive strategies for the indoor environment adjustment (i.e. thermostats, windows and shading operation), especially in a climate with generally mild summers. The absence of personal environmental control (PEC) on natural ventilation and air-change is also found in the present study as the main source of dissatisfaction with air quality in CS2.

Based on these observations, the grade of PEC and people's level of adaptation to it over time, could explain why the duration of residence in Switzerland was found to also affect temperature and air quality scores. It would be interesting to complement this result with similar studies conducted in building occupied for more than 2 years, as this would allow to draw more robust conclusions on the time spent in the buildings rather than the time spent in the country. Why satisfaction with air quality in CS2 (median values) differs between climatic groups is harder to understand but could be justified again by a more tolerant attitude towards mechanical ventilation system adopted in warm climate countries.

Considering the nature of the study, a major limitation has to be acknowledged in the relatively small size of some considered samples. It cannot be excluded that more significant effects of climatic background and adaptation time could be detected in similar studies that involve a greater population.

5. Conclusions

This paper aimed at exploring the influence of climatic background and duration of residence in a country on the level of satisfaction with comfort in one's workplace. The study was conducted through a post occupancy evaluation, during which a total of 190 on-line comfort surveys were gathered from two energy-certified office buildings.

Three main conclusions can be drawn from this study:

- Climatic background was found to have a significant influence on temperature and air quality rating. Other studies (as described in the discussion section) had demonstrated the influence of climatic and geographic background on thermal comfort in outdoor environments and in test room experiments. The study presented in this paper is the first, to our knowledge, to show how crucial the comfort issue can be in multicultural workspaces. Most importantly, findings from this study led to the paradoxical evidence that environmental conditions dictated by regulations developed for a specific country and climate are more largely accepted by people with other origins. In this sense, findings suggest reconsidering existing comfort and energy guidelines for building design and operation, confirming the necessity to move towards an architecture able to be not only sustainable but also culturally inclusive.
- It was also found that temperature and especially air quality ratings tend to decrease as the duration of residence in the country increases. This type of insight supports the adaptation theory based on which the notion of comfort can vary as time goes by depending on a series of environmental and non-environmental factors. It seems that a possible explanation for occupants' increasing dissatisfaction over time is the unresolved disappointment in the level of personal control of the environment.

Consistently with the study from Nicol (2017), which concluded that people in residential buildings accept a very wide range of satisfying indoor temperatures, these outcomes – especially if complemented with further research of this kind – may suggest the need for a revision of current protocols for energy design and certification to determine acceptable indoor temperatures and systems for personal environmental adjustment, especially in mechanically conditioned buildings. Results from the current study can, for example, further encourage studies on comfort personal control systems, and more specifically on the potential of low-power devices for the control of local thermal environment that are currently conducted to provide people with systems to remain comfortable over a wider range of ambient temperatures (Zangh et al. 2015).

- Last but not least, despite not being the focus of this paper, one important finding of this study was that buildings constructed in the same period, with equivalent programs and which obtained the same energy label, can respond to users' comfort expectations in very different ways. The influence of the building design was so significant in the comfort ratings of their occupants that the option of analyzing data as a whole had to be abandoned. Results from this paper reiterate the necessity, which already emerged in several studies on energy-efficient architecture, to consider contemporary environmental design regulations as challenges to enhance our built environment rather than barriers that prevent to meet architectural quality and, above all, users' comfort and satisfaction.

6. References

Cole, R. J., Robinson, J., Brown, Z., & O'Shea, M., 2008. Re-contextualizing the notion of comfort. *Building Research & Information*, 36(4), pp. 323–336

de Dear, R.J., Brager, G.S. 1998. *Developing an adaptive model of thermal comfort and preference*. ASHRAE Tech Data Bull, 14 (1), pp. 27-49.

EU Commission, Directorate-General for Employment and Social Affairs, 2002. *High Level Task Force on Skills and Mobility: Final Report*. Office for Official Publications of the European Communities.

Fritz, C. O., Morris, P. E., & Richler, J. J. 2011. Effect size estimates: Current use, calculations, and interpretation. *Journal of Experimental Psychology: General, 141*(1), pp 2-18.

Kalmár, F., 2016. Investigation of thermal perceptions of subjects with diverse thermal histories in warm indoor environment. Building and Environment, 107, pp. 254-262.

Kenawy, I., Elkadi, H., 2013. The impact of cultural and climatic background on thermal sensation votes. In: PLEA2013, *29th Conference, Sustainable Architecture for a Renewable Future*. Munich, Germany.

Nicol, F. 2017. Temperature and adaptive comfort in heated, cooled and free-running dwellings. *Building Research & Information*,45 (7), pp. 730-744

Nicol, F., Humphreys, M., Roaf, S., 2012. Adaptive Thermal Comfort: Principles and Practice. Routledge, London; New York.

Society for Human Resource Management, 2015. Understanding Workplace Cultures Globally. Available on-line: https://www.shrm.org/

Zhang, H., E. Arens, and Y. Zhai. 2015. A review of the corrective power of personal comfort systems in non-neutral ambient environments. *Building and Environment*, 91, pp.15-41.

WORKSHOP 5

Measuring comfort in the real world

Invited Chairs:
Atze Boerstra and Adrian Pitts

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Data collection methods for accurate spatial use within rooms

Nick Van Loy[1], Ann Bosserez[2], Griet Verbeeck[3], Elke Knapen[4]

[1] Sustainability group, Faculty Architecture and Arts, University of Hasselt, Belgium, Nick.VanLoy@uhasselt.be;
[2] Sustainability group, Faculty Architecture and Arts, University of Hasselt, Belgium, Ann.Bosserez@uhasselt.be;
[3] Sustainability group, Faculty Architecture and Arts, University of Hasselt, Belgium, Griet.Verbeeck@uhasselt.be;
[4] Sustainability group, Faculty Architecture and Arts, University of Hasselt, Belgium, Elke.Knapen@uhasselt.be;

Abstract: Dwellings in Belgium are comparatively larger than residences in other countries and the occupancy rate of the living spaces is rather low. Both occupant presence and behaviour have a large impact on the actual energy consumption. Rooms are generally fully acclimatized while only part of them is used effectively which impacts the energy consumption of the dwelling. This paper discusses spatial use within rooms and a methodology to monitor the effective spatial use of dwellings. Better insights in the effective spatial use can be used to increase the space and energy efficiency, e.g. by adapting the design of the house as well as the systems for heating and ventilation to the actual spatial use. In an in-depth case study, the spatial use patterns within three single family houses are monitored during 9 consecutive days in each season. During the monitoring period, a low cost, highly accurate, ultra-wideband, indoor localisation system was used to monitor the exact location of the residents within the dwelling. In addition, the temperature, relative humidity and light intensity in each room was recorded. Each hour, the residents were asked to fill in a survey on thermal comfort, activity and operation of windows or heating systems.

Keywords: Spatial use, Occupant behaviour, Use patterns, Sustainability

1. Introduction

With an average size of 124,3 m², dwellings in Belgium are larger than in other European countries (96,0 m²) (Eurostat, 2016). However, the size of a dwelling is not always in line with the actual occupancy rate. In 2013, 39% of the dwellings in Flanders were underused, while the size of only 57,8% corresponds to the effective occupancy rate (Vanderstraeten et al., 2016). In most dwellings, rooms are completely heated while they are not completely used most of the time or even not used at all. Additionally, research shows that 25% to 34% of the energy is used while a dwelling is unoccupied (Anderson et al., 2015). This causes an unnecessary high energy consumption and a large impact on the environment.

The Energy Performance of Buildings Directive (EPBD, 2002, EPBD, 2010) aims to improve the energy efficiency and to reduce the total energy consumption of buildings. It has been proven that these building regulations have been important in reducing the energy consumption of buildings by improving the building characteristics. However, when the energy efficiency of buildings increases, the behaviour and the presence of the occupants become a more important determining factor in the actual energy consumption (Santin, 2010).

Although the phenomenon of underused dwellings and their environmental impacts is known, there are only little insights into the effective spatial use in these dwellings. The energy efficiency of these dwellings could be increased if the building, as well as the installations for heating, ventilation and lighting, are better adapted to the effective use of the buildings. Therefore, accurate information on the spatial use is required. Current research (Ryu and Moon, 2016, Yang et al., 2016, Zou et al., 2017) is mainly focusing on occupancy and the level of detail is limited to presence or absence in a room.

In this paper, a methodology is proposed to study the spatial use within rooms more in depth, including circulation and activity patterns. When studying the occupant behaviour in relation to indoor climate and energy consumption, spatial use patterns and actions of the residents should be considered; these are discussed in Section 2. In Section 3, data collection methods to monitor the occupant behaviour in dwellings are presented. In an in-depth case study, the occupant behaviour in three single-family houses is monitored by using these methods. In section 4, these methods are evaluated for correctness and completeness of the output results, and for user friendliness for the residents. First results of the spatial use and behaviour of the residents are presented.

2. Occupant behaviour in relation to indoor climate and energy consumption

To investigate the occupant behaviour in relation to indoor climate and energy consumption, spatial use patterns of residents and their interactions with the building and its installations should be considered (Figure 1). The energy for space heating is directly influenced by the use of the heating system, the use of the ventilation system, the use of appliances and the occupancy of rooms, i.e. the number of rooms which are used and the number of people inside a room (Santin, 2010). Additionally, the behaviour of the residents is affected by external factors, such as the design of the building and its characteristics (Santin, 2010) and the outdoor climate. These external factors also influence the energy consumption.

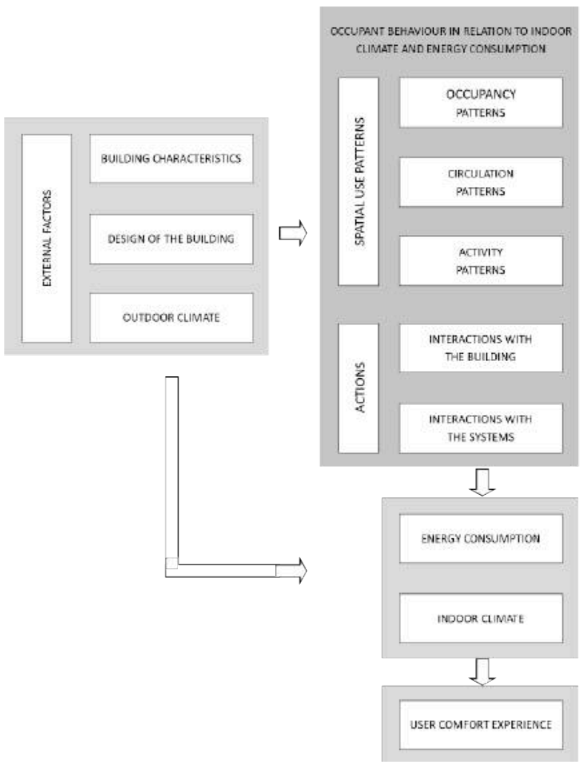


Figure 1: Impact of occupant behaviour on indoor climate and energy consumption based on the framework for occupant behaviour and energy consumption of Santin (2010).

In this paper, more factors are added (Figure 1) to the existing framework of Santin (2010). The occupancy patterns are combined with more detailed circulation patterns, which describe the exact location of the residents within a room, and activity patterns to get better insights in spatial use patterns and their impact on the energy consumption. Beside the energy consumption, the indoor climate is also affected by the occupant behaviour and the external factors. On their turn, the indoor climate will change the comfort experience of the residents which gives insights into the experience of the dwelling by the resident.

Spatial use patterns

To determine spatial use patterns in buildings, three different patterns should be considered: occupancy, circulation and activity patterns. Occupancy patterns describe the presence or absence of residents in a room during the day. Because rooms are often heated while unoccupied, the energy efficiency of buildings could be improved by better aligning occupancy and heating patterns (Anderson et al., 2015, Santin, 2010). Circulation patterns give more detailed information on the exact location of residents within a room and throughout a dwelling and on areas or zones that are most frequently used. Because mostly rooms are completely acclimatized while only a part is effectively used, also here, there is an opportunity for improvement of the energy efficiency. Activity patterns which describe the activities of the residents during the day, such as cooking, reading, etc. are needed to get insights in the activity rate which affects the actions towards the building and its installations as well as the thermal comfort experience of the residents.

Actions

Residents' interactions with the building, e.g. by opening windows and doors, and their interactions with the technical installations, e.g. by adjusting temperature settings of heating systems, ventilations rate, opening or closing valves, have a direct effect on the indoor climate and energy consumption (Andersen, 2009).

Building characteristics and outdoor climate

Besides the spatial use patterns and actions, building characteristics, such as type of dwelling, construction year, insulation level (Guerra Santin et al., 2009), and the size of the dwelling and the number of rooms (Santin, 2010) are determining factors for the energy consumption in a dwelling. Additionally, local climatic and seasonal conditions play a prominent role in the energy consumption.

3. Data collection methods

Figure 2 shows a mixed-method methodology for measuring quantitative data on residents' location and actions and room temperature as well as qualitative data on thermal comfort and activities which impacts the indoor climate and energy consumption. Five different methods are used: an indoor localisation system, a smartphone survey, sticky notes, data loggers and documentation/interviews. These are discussed in the following paragraphs.

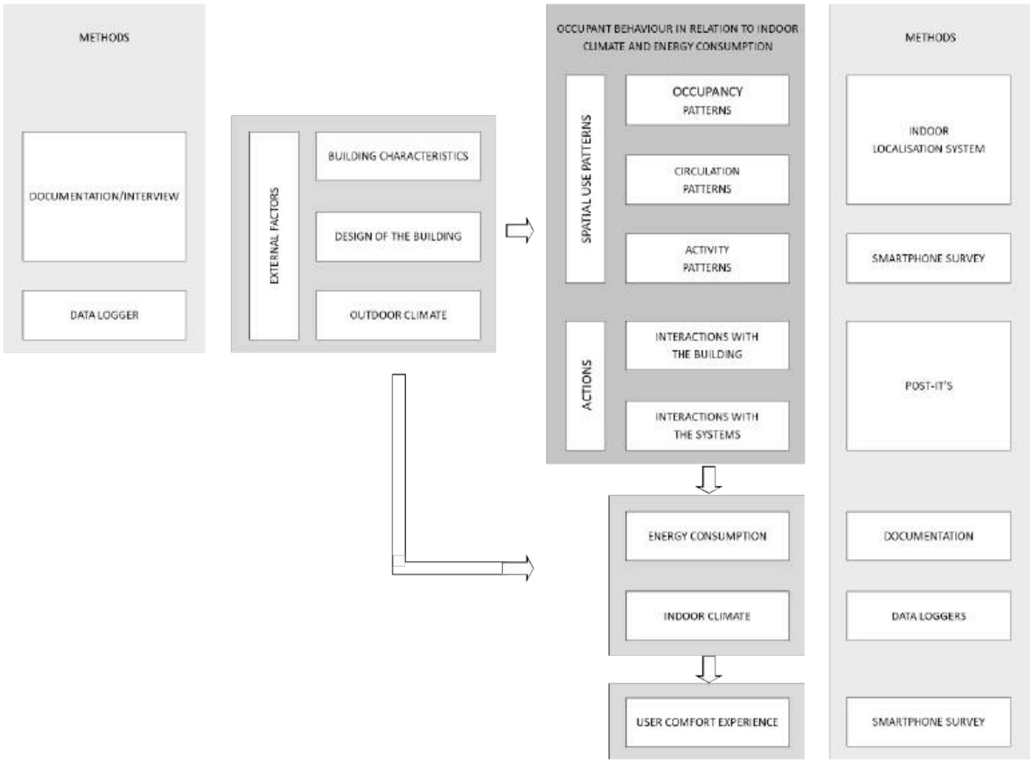


Figure 2: Methods which are used to monitor the occupant behaviour in relation to the indoor climate and energy consumption.

a. Indoor localisation system

Occupancy patterns, which only consider the presence or absence of residents in a room, can be measured by relative simple and low-cost techniques, such as passive infrared detectors or CO_2-concentration sensors in each room (Zou et al., 2017, Labeodan et al., 2015). However, to monitor the circulation patterns throughout a room or building and gain insights into the spatial use within the rooms, an indoor location system is needed which records the exact location of residents during the day.

Some boundary conditions and difficulties have to be taken into account when monitoring the indoor location of residents in dwellings. First of all, the monitoring system has to deal with a small, but very complex environment with lots of obstacles, e.g. indoor walls and furniture. In most situations, the system has to work in non-line-of-sight, where the direct signal is obstructed, and in a multipath environment, where the signal reaches the antennas ("anchors") in multiple ways caused by reflection, these conditions can lower the accuracy dramatically, depending of the positioning algorithm that is used. Due to the small size of dwellings, the system has to be accurate enough (min. accuracy 1 m) because small errors in accuracy can lead to large errors in the results, such as presence in another room. In literature (Mautz, 2012, Alarifi et al., 2016), it is found that an ultra-wideband based system gives the best results in such environments.

For this research, a low-cost cost indoor localisation system, Pozyx (Pozyx, 2017), is used, which provides high accurate positioning and motion (accelerometer, gyroscope, magnetometer, pressure sensor) information, and is compatible with the open-source Arduino platform. The system consists of minimum four anchors (figure 3 $_{left}$) (for three-dimensional localisation), one tag for each resident (figure 3 $_{middle}$) and one master tag (figure 3 $_{right}$) to control and readout the data of the tags. The number of anchors needed for accurate localisation monitoring depends on the design of the building and it's structure (walls, materials, e.g.) and has to be tested during set up. In general, 4 anchors are needed per floor, but the presence of f.e. dense walls results in a higher number of anchors to achieve the accuracy. Each person which has to be monitored, has to wear a tag. In case more persons have to be located at the same time, the tags have to be managed by one master tag. The master tags sends signals alternately to the different tags to initialize the localisation algorithm and to gather all the results.

For the ease of wearing, a case is designed (figure 3 $_{\text{middle}}$) which contains the tag, a battery, a charger and a switch. Residents can wear the case in two different ways: with a clip on a belt or with a lanyard. Theoretically, the autonomy of the tag is 18 hours, but this depends on different factors, such as the building layout, the building characteristics, etc..

Figure 3: modules to locate multiple persons. Anchor (left) with a fixed and know position, tag (middle) which has to be weared by the residents, mastertag (right) which manages the tags and gathers the location of the residents on SD.

b. Sticky notes

To monitor all residents' interactions with the building as well as the interactions with the systems digitally, a lot of sensors would be needed. Therefore, pre-printed sticky notes are used (Figure 4) and placed on every window, door and heating element. Residents are asked to fill in the date and hour when they open or close the window or door to ventilate the dwelling. Interactions with the systems are only noted when the residents operate the valves of heating elements or when they change the thermostat settings. When a programmable thermostat is used, these settings are taken into account and residents only have to make a note when they make changes to the pre-set program.

Openen van ramen/deuren	Ruimte:_________		Gebruik van verwarming	Ruimte:_________	
Dag: ___/___	Uur: ___:___	0 Open 0 dicht	Dag: ___/___	Uur: ___:___	0 Aan 0 Neut 0 Uit
Dag: ___/___	Uur: ___:___	0 Open 0 dicht	Dag: ___/___	Uur: ___:___	0 Aan 0 Neut 0 Uit
Dag: ___/___	Uur: ___:___	0 Open 0 dicht	Dag: ___/___	Uur: ___:___	0 Aan 0 Neut 0 Uit
Dag: ___/___	Uur: ___:___	0 Open 0 dicht	Dag: ___/___	Uur: ___:___	0 Aan 0 Neut 0 Uit
Dag: ___/___	Uur: ___:___	0 Open 0 dicht	Dag: ___/___	Uur: ___:___	0 Aan 0 Neut 0 Uit
Dag: ___/___	Uur: ___:___	0 Open 0 dicht	Dag: ___/___	Uur: ___:___	0 Aan 0 Neut 0 Uit
Dag: ___/___	Uur: ___:___	0 Open 0 dicht	Dag: ___/___	Uur: ___:___	0 Aan 0 Neut 0 Uit
Dag: ___/___	Uur: ___:___	0 Open 0 dicht	Dag: ___/___	Uur: ___:___	0 Aan 0 Neut 0 Uit
Dag: ___/___	Uur: ___:___	0 Open 0 dicht	Dag: ___/___	Uur: ___:___	0 Aan 0 Neut 0 Uit

Figure 4: Pre-printed sticky notes to write down the residents' actions

c. Data loggers

Data loggers onset Hobo u12-012 (onsetcomp, 2017) are used to monitor the indoor temperature, relative humidity and the light intensity. These data are collected with a 15-minute interval in each room which is used during the monitoring period. Data loggers must be located away from the windows to avoid the influence of the outdoor environment and they are placed on a height between 1-1,5m above the floor where people are living. The outdoor climate (temperature, relative humidity and light intensity) is measured at the same time as the indoor climate.

d. Thermal comfort survey

To qualitatively evaluate the thermal comfort of the residents, they are asked to fill in a survey. The survey is based on existing surveys on thermal comfort which consider the indoor temperature, relative humidity, air movement, activity level and clothing insulation of the residents (Guerra-Santin and Tweed, 2015, Wang et al., 2017, Kim et al., 2017, Wong and Shan, 2003).

Guerra-Santin and Tweed (2015) distinguish three different types of questionnaires: retrospective questionnaires (residents are asked about their comfort every week, month or year), real-time questionnaires (residents are asked about their comfort on the moment itself in the room where they are) and seasonal thermal comfort questionnaires (residents are asked about their comfort every season). With a retrospective questionnaire and a seasonal comfort questionnaire, it is possible to ask the comfort of the resident over a longer period and multiple rooms, but the resident might not be totally objective. The real-time questionnaire seems to be the most reliable and most accurate, because the resident has to assess his comfort at the moment itself and the answers can be coupled with the measured indoor climate data. However, this method is also the most time consuming. Therefore, in this research, a survey was set up as a "right here, right now" survey, which means that the residents have to fill it in on that moment and the place where they are at that moment (Manu et al., 2016).

The questionnaire consists of following questions:

- In which room are you?
- Which activity are you doing?
- How do you experience the indoor temperature at this moment?
- What type of clothes are you wearing?
- Do you have any comments on the indoor climate (air quality/air humidity/smell). If so, which?

The qualitative data of the survey are complementary to the data measured on location and indoor climate and can be coupled because the time is recorded as well. To accomplish a regular response rate, the residents received a SMS message each hour to remember to fill in the survey (Kim et al., 2017). It takes less than one minute to complete the questionnaire. The survey is available on an offline application on the smartphone of the residents, as it has to be possible to fill in the survey on the moment itself either when there is no internet available.

e. Interview/Documentation

The plans of the dwellings were collected to obtain insights into the design of the building and building characteristics, which were complemented with interviews to get insights into the use of the building by the residents. The residents have to fill in a short questionnaire with questions about themselves, e.g. their age, number of family members, their job, as well as their week schedule to get a first insight in their presence in the dwelling. Thereafter, they are interviewed about their use and experience of the building as a whole. During a subsequent walkthrough interview, residents provided insights on the function, use and experience in each room. The walkthrough interview allows the resident to clearly describe the use and experience of the room (Watson and Thomson, 2005).

4. Case study analysis

a. Description of the cases

The methods to monitor the occupant behaviour in relation to the indoor climate and energy consumption, which are discussed in this paper, are tested and evaluated by analysing the spatial use and energy consumption in three single-family houses. After each monitoring period, the methods are fine-tuned.

The three houses are large and under-utilized because only two residents are permanently living in the dwelling. Table 1 shows the main characteristics of the households and their dwellings.

Table 1: household and dwelling characteristics

	Dwelling 1	Dwelling 2	Dwelling 3
Household size (family size)	1	5 (3 children half-time inhabitants)	2
Occupation	Employed	Employed Self-employed 3 Students (absent from Monday to Friday)	Employed Employed
Type dwelling	Detached	Detached	Semi-detached
EPC*	496 kWh/m²year	Unknown	370 kWh/m²year
Surface (total/living)	167m²/89,3m²	396m²/204m²	217m²/140m²
Construction year	1990	Before 1945	Before 1945

(*the Energy performance coeficient shows how many energy a building is using. the score depents on the insulation level and installations but does not take the occupant behaviour into account. therefore this score can be different of the real energy consumption)

During nine consecutive days in each of the four seasons of the year, the spatial use, indoor climate and actions are monitored and the residents' activities and comfort experience are asked for with the methods described in Section 3. After each monitoring period, the data are evaluated on completeness and correctness by comparing the data with the insights gathered by the interviews. The residents are also asked to give feedback on the tasks they had to complete, such as wearing the localisation system, making notes of their actions and filling in the survey. Some results of the data analysis are presented in Section 4.c.

f. Evaluation of the data collection methods indoor localisation system

The raw data output from the indoor localisation system are X, Y, Z-coordinates with an ID- and time-stamp. These data need to be filtered because of errors when the signal between the tags and the anchors is too weak, which leads to inaccurate results, or when the residents are out of the system's coverage area, which mostly results in zero-values. When the filtered data are plotted on the floorplan of the dwelling, all locations where the residents have walked through or have been for a longer time, e.g. during an activity, can be visualized (Section IV.d).

During the monitoring period, the residents continuously have to wear the tag when being at home, which might be rather intrusive. After the first monitoring period, the tags were redeveloped and made smaller and lighter. During the second monitoring period, questions raised about the place where the residents had to place the tag when it was annoying to have it with them, e.g. while cooking. Problems about the autonomy showed up in the redeveloped tags, especially during the weekend when the residents typically spend more hours at home; they did not reach the 18 hours of autonomy as calculated and it took too long to reload the battery. A chest belt is provided, because some of the residents mentioned that the tag was difficult to wear in some situations, e.g. during cooking. In the future, the tracking system could be made smaller to make it less intrusive to the residents.

Sticky notes

The sticky notes are used to collect all residents' interactions with the building and the systems. Although sometimes the residents forget to fill in the sticky notes, they give a good and a detailed picture of the actions of the residents in the whole building.

So, only a few sticky notes were left after the monitoring period. After the first monitoring period, one of the residents explained that she changed her behaviour because of the sticky notes. For example windows that would be opened are now kept closed because of the time that needs to be invested in noting it down. This shows that it is important to interview the residents after the monitoring period and to ask them if and eventually in which way the data collection methods have changed their behavior during the monitoring.

Survey

Because only every hour a reminder is sent to fill in the survey, qualitative data on the experience of thermal comfort is only available on certain moments in certain rooms. However, the survey is mostly filled in in rooms where the residents are staying for a longer time and gives thereby a good insight in how the residents experienced the indoor climate. By increasing the frequency of reminders, more information could be collected, but it would be more intense for the residents with the risk of dropping out or non-response.

The residents have to install an application for the survey on their own smartphone, which is tested together with the residents and they can ask questions about aspects that are not clear to them. Although the survey is based on existing surveys, there were some questions about activities which were not specific enough for the residents and the possible choices of clothing were difficult to note. The residents need a smartphone because they have to fill in the survey on the moment itself. Some residents do not wear their smartphone with them the whole day, for them this is an extra effort. Remarks of the residents showed that too many reminders are sent (each hour), e.g. when they are not at home, but they can easily be ignored when these are unnecessary.

Data loggers

The data loggers are recording the temperature, the relative humidity and the light intensity every 15 minutes and are placed in the rooms used by the residents, which gives the opportunity to couple the indoor climate with the thermal comfort.

Overall feedback of the residents

During the feedback interview after each monitoring period, the residents mentioned that the period is intensive, but there was not one specific part which was the most intrusive for all residents. Some of the residents found the tracking system annoying, while for others the sticky notes were too time-consuming. Also the combination of wearing the tag for the indoor localisation system and their smartphone was very difficult.

g. Results of the data collection methods

The spatial use patterns in three dwellings and their impact on energy consumption and indoor climate are monitored during four seasons. As an illustration of the information that is gathered by the data collection methods, discussed in this paper, some results are presented here.

Localisation data

By plotting the localisation data as a heat map on the floorplan, the area of the room which is used and the places where the residents have been the most can be determined. Figure 5 shows a heat map of the localisation data of respectively resident 1 and resident 2 during one complete monitoring period. The dots are showing all recorded data. The colour changes from yellow to red when the density of the recorded data is higher. Both figures show that the room at the right-top is not really used, which corresponds to the description of the residents that this room is only used to open or close the windows. Also, differences in use between the two residents can be observed, e.g. the room at the right-bottom is especially used by resident 2, while resident 1 rarely comes in this room. The top part of the left-top room is also rarely used, which shows that the detail of the circulation patterns is relevant to analyse to indoor climate and energy consumption, in contrast to the occupation patterns which would mark the whole room as occupied.

Although a heat map shows the location of the residents throughout a certain period, this gives no insight in the zones where the residents stay the most. E.g. when the residents pass multiple times through the hallway, this gives the same result in a heat map as when the residents are staying on one place for a longer time. To determine the places within a room where the residents are staying, "stops" have to be defined. Based on literature (Cich et al., 2016), stops can be seen as locations where the residents are standing still for a longer time and these locations are related to an activity. In further research, insights in the residents' activities in specific rooms will be derived from the survey and the interviews. These will be used to define stops and identify the zones where residents stay for longer periods.

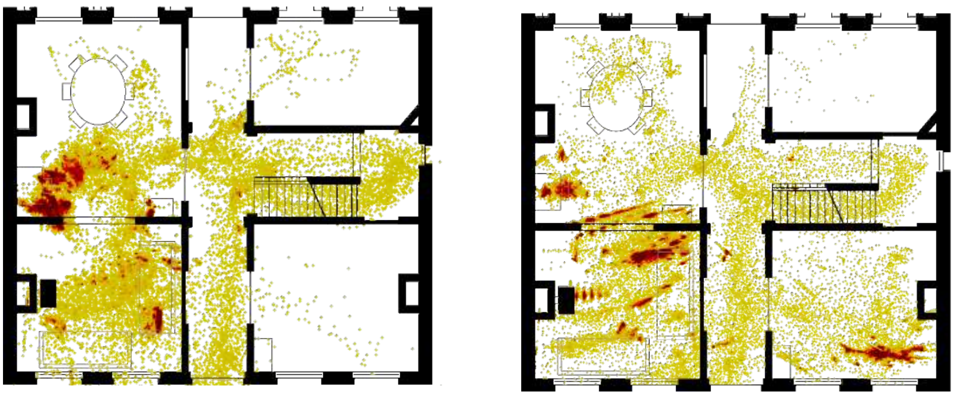


Figure 5: Spatial use of resident 1 (left) and resident 2 (right) on the ground floor of dwelling 2 during 9 consecutive days presented as a heat map

Combined data on occupancy, actions, indoor climate and comfort experience

Data on occupancy, actions, indoor climate and comfort experience of the residents are time-related and can be combined on a timeline for each room in the dwelling. Such a timeline (e.g. Figure 6) shows the occupancy of the room, if the room is heated and/or ventilated, the indoor climate of the room and the comfort experience of the residents. This combined timeline gives insights in how the room is used during a certain period and can be analysed to identify inefficiencies, e.g. when the room is heated while the room is not used or is only partly used. The comfort rating can be related to the actual indoor climate and the residents' interactions with the building or systems to change the indoor climate. In Figure 6, a timeline with data of a 3-day monitoring period in the office space of dwelling 2 is presented. It shows that the room is only used for shorter periods and is ventilated by opening the windows, even when the room is unoccupied. The heating is not used during this monitoring period (summer). As mentioned before, the thermal comfort rating is only collected at certain moments in time. During these 3 days, the resident only noted down once his thermal comfort. As he was comfortable in this room, he did not take any actions to change the indoor climate.

This timeline can be combined with the localisation data of the periods of occupancy which show the spatial use of the room in each of these periods. Five heat maps with localisation data of resident 2 are added to Figure 6: in heat map 2 and 4, the resident has only used a part of the room (at the book shelf and at the desk) while, in the first and the last heat map, the resident has used a larger part of the room. In heat map 3, the resident only stayed in the room for a short period of one minute. These combined data on localisation, actions, indoor climate and comfort experience, can be used to determine spatial use patterns and identify inefficiencies in energy and spatial use.

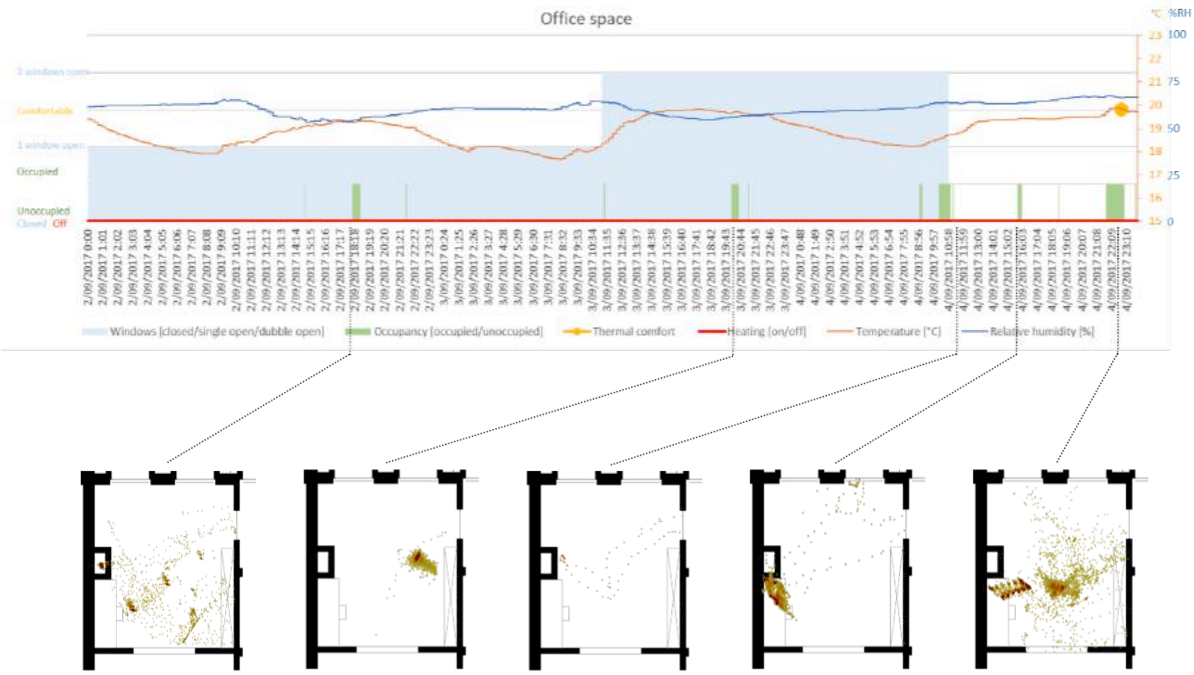


Figure 6: Timeline during 3 days from resident 2 in the office space of dwelling 2: combined data on occupation, actions, indoor climate, comfort experience and spatial use

5. Conclusion

In this paper, a mixed-method methodology to monitor occupant behaviour in relation to the indoor climate and energy consumption is presented. Five different methods are combined, i.e. an indoor localisation system, a smartphone survey, sticky notes, data loggers and documentation/interviews. Quantitative data on spatial use patterns, interactions with the buildings and systems and indoor and outdoor climate are obtained, as well as qualitative data on activity patterns and thermal comfort experience. Although the monitoring period is relatively intense for the residents, the data collection methods give good insights in the whole use of a dwelling. First results show that the methodology gives a fine-graded overview of the residents' spatial use within a room. By combining data of several methods discussed in this paper, further insights on spatial use in relation to energy consumption and thermal comfort experience can be obtained. These insights will be used to identify inefficiencies in spatial use and to optimize the energy efficiency.

6. References

Alarifi, A., Al-Salman, A., Alsaleh, M., Alnafessa, A., Al-Hadhrami, S., Al-Ammar, M. A. & Al-Khalifa, H. S. 2016. Ultra Wideband Indoor Positioning Technologies: Analysis and Recent Advances. *Sensors,* 16**,** 36.

Andersen. 2009. *Occupant behaviour with regard to control to the indoor environment.* PhD, Techical university of Denmark.

Anderson, K., Song, K., Lee, S., Lee, H. & Park, M. 2015. Energy consumption in households while unoccupied: Evidence from dormitories. *Energy and Buildings,* 87**,** 335-341.

Cich, G., Knapen, L., Bellemans, T., Janssens, D. & Wets, G. 2016. Threshold settings for TRIP/STOP detection in GPS traces. *Journal of Ambient Intelligence and Humanized Computing,* 7**,** 395-413.

EPBD 2002. Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. .

EPBD 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast).

EUROSTAT. 2016. *Average size of dwelling by household type and degree of urbanisation* [Online]. [Accessed].

Guerra-Santin, O. & Tweed, C. A. 2015. In-use monitoring of buildings: An overview of data collection methods. *Energy and Buildings,* 93**,** 189-207.

Guerra Santin, O., Itard, L. & Visscher, H. 2009. The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy and Buildings,* 41**,** 1223-1232.

Kim, J., De Dear, R., Parkinson, T. & Candido, C. 2017. Understanding patterns of adaptive comfort behaviour in the Sydney mixed-mode residential context. *Energy and Buildings,* 141**,** 274-283.

Labeodan, T., Zeiler, W., Boxem, G. & Zhao, Y. 2015. Occupancy measurement in commercial office buildings for demand-driven control applications—A survey and detection system evaluation. *Energy and Buildings,* 93**,** 303-314.

Manu, S., Shukla, Y., Rawal, R., Thomas, L. E. & De Dear, R. 2016. Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). *Building and Environment,* 98**,** 55-70.

Mautz, R. 2012. *IndoorPositioning Technologies.* ETH Zurich.

ONSETCOMP. 2017. *HOBO Temperature/Relative Humidity/Light/External Data Logger* [Online]. Available: http://www.onsetcomp.com/products/data-loggers/u12-012 [Accessed].

POZYX. 2017. *Pozyx Accurate positioning* [Online]. Available: https://www.pozyx.io/ [Accessed 19 december 2017].

Ryu, S. H. & Moon, H. J. 2016. Development of an occupancy prediction model using indoor environmental data based on machine learning techniques. *Building and Environment,* 107**,** 1-9.

Santin, O. G. 2010. *Actual energy consumption in dwellings: The effect of energy performance regulations and occupant behaviour.* Doctor, University Delft.

Vanderstraeten, L., Vanneste, D. & Ryckewaert, M. 2016. Grote Woononderzoek 2013. Leuven.

Wang, Y., De Groot, R., Bakker, F., Wortch, H. & Leemans, R. 2017. Thermal comfort in urban green spaces: a survey on a Dutch university campus. *Int J Biometeorol,* 61**,** 87-101.

Watson, C. & Thomson, K. 2005. Bringing post-occupancy evaluation to schools in scotland.

Wong, N. H. & Shan, K. S. 2003. Thermal comfort in classrooms in the tropics. *Energy and buildings,* 35**,** 15.

Yang, J., Santamouris, M. & Lee, S. E. 2016. Review of occupancy sensing systems and occupancy modeling methodologies for the application in institutional buildings. *Energy and Buildings,* 121**,** 344-349.

Zou, H., Jiang, H., Yang, J., Xie, L. & Spanos, C. 2017. Non-intrusive occupancy sensing in commercial buildings. *Energy and Buildings,* 154**,** 633-643.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Thermal Comfort Assessment Based on Measurement and Questionnaire Surveys in a Large Mechanically Ventilated Space

Ali Alzaid[1], Maria Kolokotroni[1], Hazim Awbi[2]

[1] Mechanical Engineering, Brunel University London
Uxbridge, Middlesex UB8 3PH, UK, lg15aaa4@my.brunel.ac.uk
Maria.kolokotroni@brunel.ac.uk
[2] School of Built Environment, University of Reading
Reading RG6 6UA, UK, h.b.awbi@reading.ac.uk

Abstract: This paper presents a thermal comfort study in a large occupied office (floor-to-ceiling height >5m) ventilated by a simple mixing ventilation system. The evaluation was conducted during the summer seasons of 2016 and 2017 using three different tools; (a) long term monitoring, (b) short term detailed measurements and (c) occupant questionnaire. Long term monitoring included air temperature and relative humidity at several locations and heights within the space with external conditions retrieved form a weather station on the roof of the building. The short term spot measurements included air temperature, relative humidity and air speed each at three vertical occupancy heights and the inlet diffusers. The surveys involved collection data using questionnaires developed based on ISO 10551. Analysis of long term data using temperature clouds indicate that the building can be approximated to be free running. A comparison between the measurement (analysed using PMV/PPD and adaptive thermal comfort) and the questionnaire surveys' results show good agreement between predictions and occupant evaluation. The existing ventilation system was able to meet the requirement for thermal comfort in this large enclosure. However, with regards to the air movement, it did not achieve the recommended levels and this has affected occupant responses.

Keywords: Large space, Thermal comfort, Experimental measurement, occupant questionnaire

1. Introduction

Ventilation of large spaces differs from that for spaces with a small volume, especially those with ceiling height of 3m or less. According to Li et al. (2009), an enclosure with more than 5 meters floor-to-ceiling height can be considered as a large space. In such spaces, when warm air under the effect of buoyancy rises, a positive temperature gradient between floor and ceiling is formed, known as stratification (Calay et al. 2000) and the air flow pattern should be arranged and controlled to ensure an acceptable indoor air quality and thermal comfort in the occupied zone without the need for excessive air flow rates (Heiselberg et al. 1998). Mateus & Carrilho da Graça (2017) carried out an extensive literature survey of HVAC systems' performance in large spaces; they found that three types of room air distribution strategies are commonly used. These are displacement ventilation, mixing ventilation and underfloor air distribution systems. Furthermore, their review revealed that very few studies are available which make a comparison between ventilation model simulations and measured air temperature in large spaces. These measurements are needed for commissioning, diagnostic and assessment purposes. However, the considerable volume and envelope area associated with large spaces add to the difficulty of measurements (International Energy Agency (IEA) 1998).

The goal of any ventilation system is to create a suitable microclimate in the ventilated place. In this case, microclimate refers to the thermal environment and air quality. These two factors are essential to the comfort of the occupants of the spaces (Awbi 2003). The thermal balance can be affected by several factors which are physical activity, clothing resistance and environmental parameters such as air temperature, mean radiant temperature, air humidity and air velocity. To predict the thermal sensation for the body as a whole, the Predicted Mean Vote (PMV) index can be used for estimating or evaluating the above factors. The percentage of the people who are dissatisfied with the thermal environment is measured by Predicted Percentage Dissatisfied (PPD) index. Furthermore, thermal discomfort can be generated by unwanted heating or cooling of one nominated segment of the body. This is known as local discomfort and can be caused by four factors which are draft, vertical air temperature differences, radiant temperature asymmetry and cold or warm floors (BSI 2005).

In parallel, the adaptive model of thermal comfort is also used to estimate comfort conditions. It starts with behavioural adaptation which is made by people to stay comfortable rather than comply with the theory of heat exchange. Such adaption is a two-way process. The person adapts himself to suit the environmental by such action like changing clothes. He also adapts his thermal environment to suit himself by opening windows or adjusting the heating or cooling provision (Humphreys et al. 2013). A recent review study by Nicol (2017) shows that a very wide range of indoor temperature is found in mechanically controlled buildings. The paper explained this range using the adaptive approach, considering mechanical conditioning systems as a robust adaptive way used by occupants to control the indoor temperature to their various climate, building and lifestyles. The study proposed that the current indoor temperatures guidelines in dwellings can be adjusted to be more flexible.

This paper presents a thermal comfort study for a large occupied open plan office located in south England during the summer season for the years 2016 and 2017. This large office is supplied by a mechanical overhead mixing ventilation cooling system which operates during the summer months. The purpose of the survey is to understand the thermal conditions provided by the current ventilation system with measurements analysed in terms of current thermal comfort guidelines and research findings for buildings which are not free running (FR) and relate these to occupants' satisfaction.

2. Description of the case-study and ventilation system

A large open plan office used by research staff and students was chosen as the case-study of large space because its floor-to-ceiling height is 6m.The enclosure has dimensions of 15.5m x14m x 6m and a floor area of 201 $\mathbf{m^2}$ with brick external walls and metal roof which includes two large skylights. Two big rectangle windows are located on the south facing wall of the building with dimensions 3.5m x 1.1m and 4.2m x 1.1m. There is one door at each end wall of the building. The large open plan office includes 12 personal computers, peak occupancy of 12 occupants in summer 2016 while there were 24 personal computers and 24 occupants in summer 2017. It also includes artificial lighting comprising of 46 luminaires each equipped with two 49 W lamps. The total internal heat gain in the office was 27 W/$\mathbf{m^2}$ in summer 2016 while it was 42.8 W/$\mathbf{m^2}$ in summer 2017. Furthermore, the external heat gain due to solar radiation has a substantial impact on the performance of the ventilation system in the office and on the thermal comfort as well. Thus, the solar heat gain through the office's ceiling and absorbed and passing through the office' windows were 1130W and 1803W respectively calculated for one representative hour in the summer.

The office is equipped with a mechanical cooling overhead mixing ventilation system which operates during the summer months. The external air is delivered into the building interior through a 13m long cylindrical supply duct with 0.7m diameter. This duct has eight air diffusers located at a height of 3.7 m above the floor with dimension of 0.8m x 0.15m and divided into seven segments. Air exhaust is via two return grills located at a height of 3.7m with dimensions 1.0m x 0.5m each, see Figure 1.

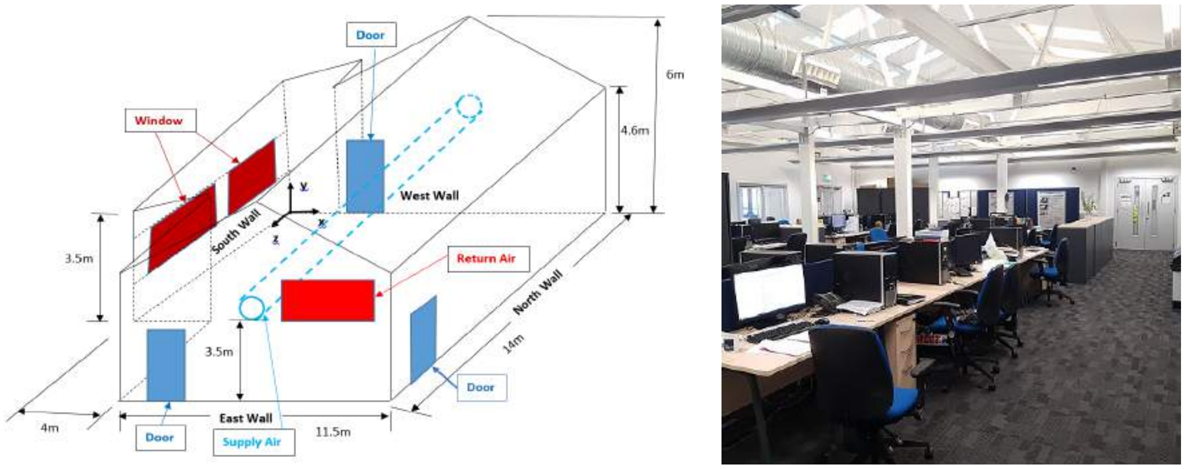


Figure 1. Sketch and photo of the researchers' office at studied building.

The measurements were carried out during the summer of 2016 over a period of 28 days from 24/8/2016 to 21/9/2016 which can be considered late summer season in London. During this period and according to the weather station mounted on the building (about 3m above the roof), the external average temperature was 18.5˚C, the maximum was 28.9˚C, the minimum temperature was 11.3˚C while solar radiation reached a maximum of 740 W/m^2. On the other hand, the external average relative humidity for the same periods was 80%, the maximum was 100% and the minimum was 39.4 %.

For the summer of 2017, measurements were carried out for three months from 21/6/2017 to 19/9/2017. The first month started from 21/6/2017 to 19/7/2017 while the second and the third months began from 22/7/2017 to 19/8/2017 and from 22/8/2017 to 19/9/2017 respectively. During this period the mean outdoor temperature was 17.3˚C, the maximum was 34.7˚C, and the minimum temperature was 6.6˚C while solar radiation reached 943 W/m^2. On the other hand, the outdoor air was generally humid with an average relative humidity of 75.6%, the maximum of 99.8% and the minimum of 30.2 %. In general, these periods of the year can be considered the hottest months in London.

3. Methodology

Thermal comfort in this large open plan office was evaluated using three different tools which were: long-term monitoring during the summer of 2016 and 2017, spot detailed measurements for a short time in summer 2016 and 2017 and occupant questionnaire surveys only in summer 2017.

3.1. Long-term monitoring survey

Air temperature and relative humidity were measured using nine HOBO Temp/RH data loggers attached to three columns (C1, C5 and C8) which are located at three different heights of 0.1, 1.2 and 1.8m, for measuring the temperature and relative humidity distributions between the floor and standing height, see Figure 2. In addition, eight HOBO Temp/RH data loggers were used to measure the air temperature at the eight diffusers and four more loggers were mounted at heights of 4m and 5m in two different locations to measure the air temperature and relative humidity in the area above the occupied zone. The accuracy of the air temperature measurement is ± 0.21˚C and ± 3.5% for the relative humidity measurements (HOBO n.d.).

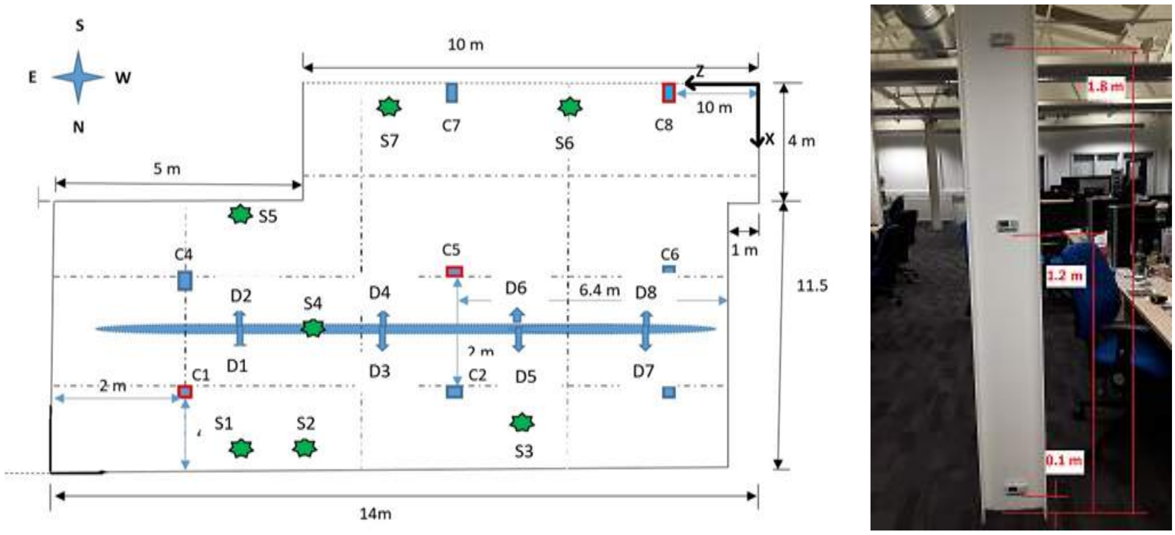


Figure 2. Schematic layout of the researchers' office building and HOBO Temp/RH data logger location attached to the columns (C1, C5, C8) at three different heights of 0.1, 1.2 and 1.8m. S1-S7 are the location of spot measurements while D1-D8 indicates the location of the diffusers.

3.2. Spot detailed measurement survey

The spot detailed measurements were carried out during two summer seasons. The measurements were conducted in the summer of 2016 over five days from 5/9/2016 to 9/9/2016 at three different times of a day (11:00, 13:00 and 15:00). In the summer of 2017, the measurements were performed over three days on 31/8/ 2017, 5/9/2017 and 11/9/2017. The environmental parameters were obtained for seven different spots as shown in Figure 2, chosen to represent typical positions of the occupants. At each spot, measurements of air temperature, air speed, and relative humidity were taken at heights of 0.1m (foot level), 1.2m (head level of a seated individual) and 1.8m (head level of a standing individual) above the floor**.** These parameters were measured over two minutes with a sampling interval of ten seconds by using a TA465 AirFlow instrument. The accuracy of the air speed measurement is estimated to be ± 0.015 m/s or ± 3% while the error of measured temperature is estimated to be ± 0.3 ˚C. In addition a CPS Thermo Anemometer AM50 were used to measure the air speed at the eight diffusers for two different days 31/8/2017 and 11/9/2017 at 13:00 where the accuracy of this anemometer was ± 3%. The air speed at the eight diffusers were also measured twice in the summer of 2016 by using the TA465 AirFlow instrument on 6/9/2016 and 8/9/2016 at 13:00.

3.3. Questionnaire survey

The research staff who work at the open-plan office investigated were recruited for this study in summer 2017. The participants consisted of young females and males who have various ethnic origins and nationalities.The subjective study involved collection of data using questionnaires which were developed on the basis of ISO 10551 (BSI 2007) and guided by recent literature (Ricciardi et al. (2016) Zhao et al. (2017)) . The questionnaire was developed to assess the thermal environment based on the occupant's thermal sensation vote and air movement in the office. This assessment will be made based on judgements at the head and foot levels and overall comfort sensation as well as an individual preference for different conditions. ASHRAE seven points thermal sensations scale (from – 3 to +3) were used to evaluate thermal sensations and rate the impressions of comfort with regard to air movement. This is to collect the quantified thermal sensation of the occupants. A similar seven-point scale is used for the thermal preference vote for direct comparison with the thermal sensation vote. The freshness of air was used to assess the air quality inside the office. The questionnaire also addressed the clothing garments for the participants to obtain the clothing insulation value. In addition to that, the participants had to indicate their location on the office's plan. The rating scales for these parameters are shown in Table 1. Besides that, PMV, PPD and several other aspects were considered to elaborate the questionnaires as proposed by Ricciardi et al. (2016), (Ricciardi & Buratti 2015) and (Buratti & Ricciardi 2009) see Table 2. The subjects were required to make only one choice from the scale for each question. Both questionnaire distribution and measurements were carried out at 15:00 each day, in order to allow the participants to adjust to the environmental condition after the lunch break.

Table 1. Rating scales for subjective evaluation parameters

Parameters	**Rating Scales**						
	-3	**-2**	**-1**	**0**	**+1**	**+2**	**+3**
Thermal Sensation (TS)	Cold	Cool	Slightly cool	Neither hot nor cold	Slightly warm	Warm	Hot
Thermal Preference (TP)	Much cooler	Cooler	Slightly cooler	Without change	Slightly warmer	Warmer	Much warmer
Air Movement (AM)	Very still	Still	Slightly still	Acceptable	Slightly draughty	Draughty	Very draughty
Air movement Preference (AMP)	Much more air movement	More air movement	Slightly more air movement	Without change	Slightly less air movement	Less air movement	Much less air movement
Relative Humidity (RH)	Very dry	Dry	Slightly dry	Neutral	Slightly humid	Humid	Very humid
Relative Humidity Preference (RHP)	Much drier	Drier	Slightly drier	Without change	Slightly more humid	More humid	Much more humid
Thermal Comfort (TC)				Comfortable	Slightly comfortable	Uncomfortab le	Very uncomfortable
Air quality (AQ)	Very fresh	Fresh	Slightly Fresh	Neutral	Slightly stuffy	Stuffy	Very stuffy
Air Quality Preference (AQP)				Acceptable	Slightly acceptable	Unacceptable	Very unacceptable

Table 2. Indexes to elaborate the questionnaires

Index (%)	**Definition**	**Related Question**
Thermal dissatisfaction (TDI)	Percentage of individuals who vote, uncomfortable, very uncomfortable	What is your thermal comfort?
Thermal preference (TPI)	Percentage of individuals who vote much cooler, cooler, warmer, much warmer	What would you like to feel?
Unacceptable air movement (UAMI)	Percentage of individuals who vote very still, still, draughty, very draughty	How would you describe the air movement?

4. Results analysis

4.1. Long-term monitoring results

Figure 3 presents the temperature evolution for typical day in the summer of 2017. All indoor temperature curves remain at the same level for several hours during the night before the ventilation system is turned on at 6:00; consequently, a drop in the diffuser temperature occurred by 3 K to reach 20 ℃ and remained stable until 9:00. It follows a steady rise in the indoor air temperatures at the five heights from the beginning of working hours at 9:00 reaching a peak at 14:00 due to the heat gain inside the office. As a result, stratification condition was created in the office where the air temperatures range was 4 K between height 0.1m and 5.0m. Then the indoor temperatures curves decreased slowly and started to converge towards the end of the day. Note that the temperatures at all level inside the office increased as the outdoor temperature rises, and declined as it is declined even though the ventilation system was running at the same time.

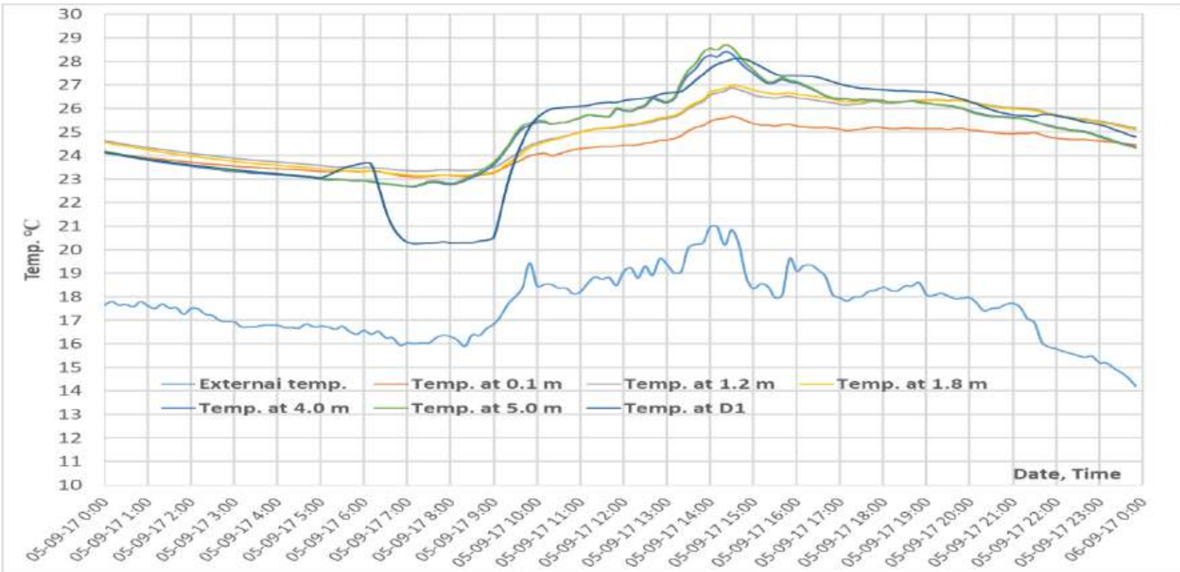


Figure 3. Air temperatures for C1 at five levels, external and diffuser D1 for one day

CIBSE TM52 (CIBSE 2013) indicates that the adaptive comfort temperature inside the free-running building is the temperature at which most of the space occupants perceive comfort, and is related to outdoor temperature over several days. In other words, it will be higher in warm weather than in the cooler case. Humphreys et al. (2013) and Nicol et al (2017) have shown that internal temperatures vary in both Free-running (FR) and mechanical heated or cooled spaces and that there is a correlation with external temperatures. They have termed such graphs as temperature clouds.

Following this approach, the indoor hourly mean temperature in the building studied is plotted against outdoor hourly mean temperature during the summer of 2016.The results are shown in the temperature cloud in Figure 4. The regression – line equation is shown in the graph while the width of the 95% interval of indoor operation temperature is 6 K.

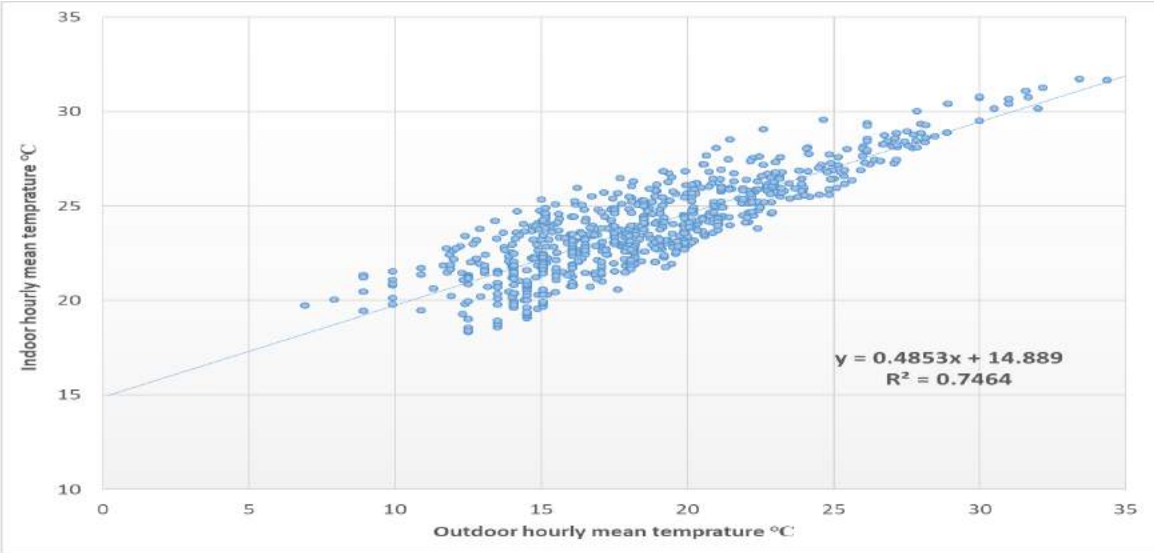


Figure 4. The mean indoor temperature versus outdoor daily mean temperature for the studied office building during summer 2016.

In the same way, the indoor temperature is plotted against outdoor mean temperature during the summer of 2017. The results are shown in the temperature cloud in Figure 5, together with the regression – line equation. In this case too, the width of the 95% interval of is indoor operation temperature 6 K.

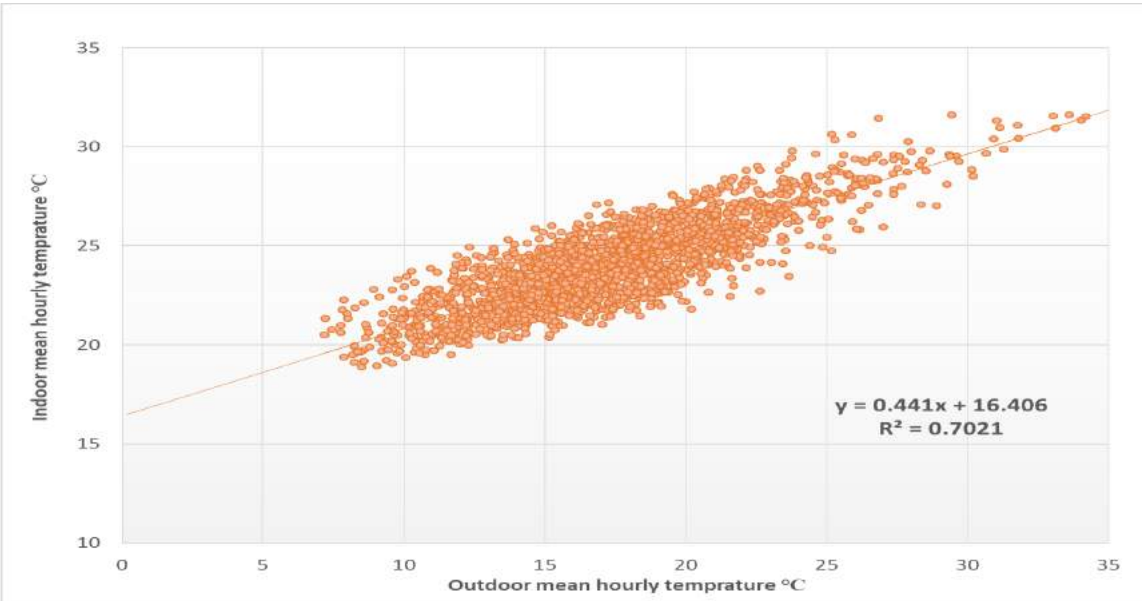


Figure 5. The mean indoor temperatures versus outdoor daily mean temperature for the studied office building during summer 2017.

Table 3 and Figure 6 compare the results from the studied office using the regression lines and equations for the summer of 2016 and the summer of 2017 with the adaptive thermal comfort lines and equations for the naturally ventilated building illustrated in European standard BS EN 15251 (BSI, 2007) and ASHRAE standard 55 (ASHRAE, 2010). Also, show the regression line and equation for a database used by Humphreys et al. (2013) at indoor and outdoor temperatures from 700 comfort surveys. These databases are called the database of thermal comfort summary statistics (DTCSS). Both office building equations have roughly the same regression coefficients. Such regression coefficient is characteristic in FR building (Humphreys et al. 2013) while it differ clearly from the gradient of the regression line for the mechanically ventilation building as introduced by Nicol (2017). The findings show that comfort in this office relates to outdoor conditions in the same way as for a FR building and not as a mechanically heated or cooled building.

Table 3. The regression line equation for different database

Database	Adaptive equations	Note	Building ventilation
Office Building (summer 2016)	$T_i = 0.48\ T_o + 14.9$	T_i is indoor temperature T_o is outdoor temperature	Mechanical
Office Building (summer 2017)	$T_i = 0.44T_o + 16.4$	T_i is indoor temperature T_o is outdoor temperature	Mechanical
European standard BS EN 15251	$T_{comf} = 0.33\ T_{rm} + 18.8$	T_{comf} is comfort temperature T_{rm} is running daily mean outdoor temperature	Free Running
ANSI/ASHRAE standard 55	$T_{comf} = 0.31\ T_{om} + 17.8$	T_{comf} is comfort temperature T_{om} is monthly mean outdoor temperature	Free Running
Humphreys et al. (2013)	$T_n = 0.53\ T_o + 13.8$	T_n is indoor temperature T_o is outdoor temperature	Free Running
Nicol (2017)	$T_i = 0.08\ T_{od} + 23.0$	T_i is indoor temperature T_{od} is outdoor temperature	Mechanical

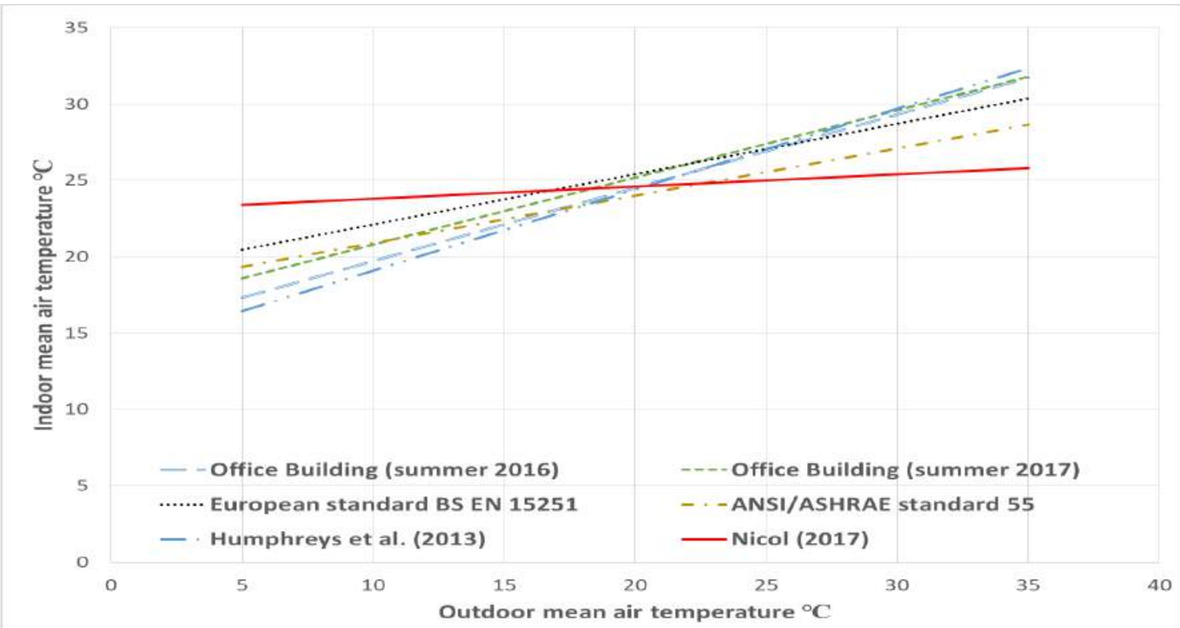


Figure 6. The regression lines for different database

Figure 7 overlays the temperature clouds for summer 2016 (figure 4) and summer 2017 (figure 5). The results show that the indoor temperatures start to rise more quickly in summer 2017 than summer 2016 as the outdoor temperature rises. Notably, both the temperature clouds together have a range of indoor temperatures of about (6-8 K) that is somewhat similar to the FR region (Nicol 2017).

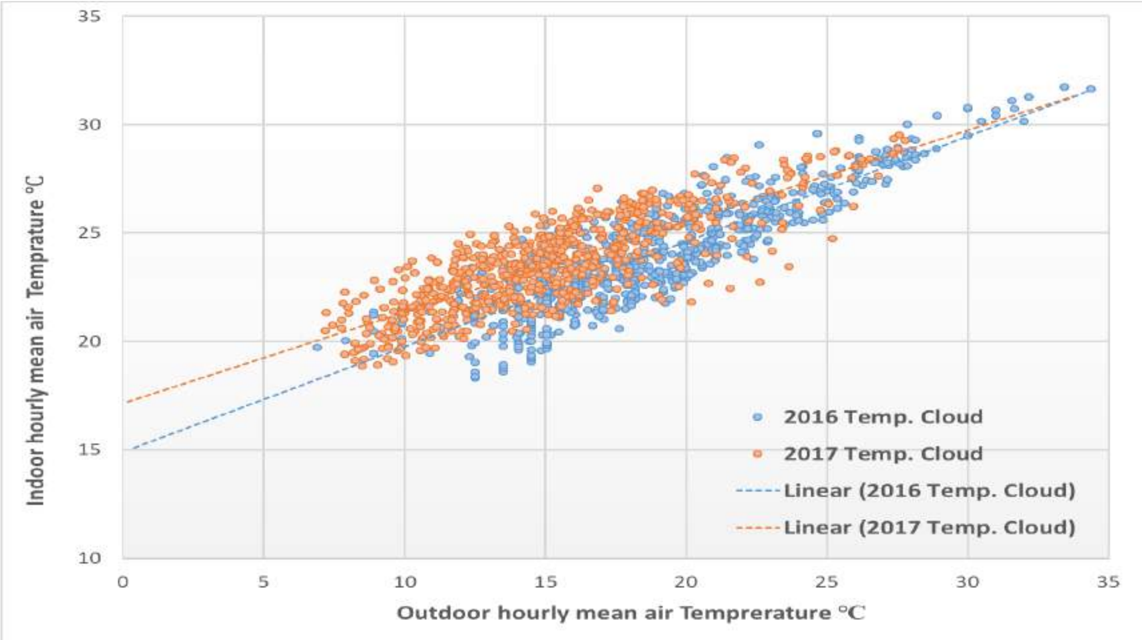


Figure 7. Overlay the temperature clouds for summer 2016 and summer 2017.

Taking into consideration the findings above we present the long term monitored temperatures of the mechanically ventilated spaces studied according to European standard BS EN15251 (BSI 2007) for FR buildings, using the equation which relates the comfort temperature to the outdoor temperature as follows:

$$\mathbf{T_{comp} = 0.33\ T_{rm} + 18.8} \qquad (1)$$

Where $\mathbf{T_{rm}}$ is the exponentially weighted running mean of the daily mean outdoor air temperature as the measure of the outdoor temperature and can be calculated by the following equation:

$$\mathbf{T_{rm} = (T_{od-1} + T_{od-2} + T_{od-3} + T_{od-4} + T_{od-5} + T_{od-6} + T_{od-7})/3.8} \qquad (2)$$

Since the office is located in renovation building the suggested category by BS EN15251 is a category (Ⅱ) where the suggested acceptable temperature range is $\pm\mathbf{3}$ K.

Figure 8 shows the hourly internal air temperatures and the thermal comfort curves during operation hours (9:00 - 20.00) for the monitoring period from 21/6/2017 to 19/9/2017. As the space studied does not include any heated or cooled surfaces, the air temperature can be approximated to the operative temperature. The number of hours $(\mathbf{H_e})$ during which $\Delta\mathbf{T}$ is greater or equal to one degree (K) above the upper thermal comfort limit during that period were 44 hours of the 936 occupied hours. Here, $\Delta\mathbf{T}$ can be defined as the difference between the indoor air temperature at any time and the upper thermal comfort temperature. The percentage of these hours was 4.7% which was higher than 3% suggested by BS EN 15251. The highest overheated hours during the measurement periods were reported on Thursday 6/7/2017 with 9 hours, followed by Wednesday 5/7/2017 with 8 hours, and Wednesday 21/6/2017 with 7 hours. The lowest overheated hours during the same period were recorded in 4 different days with 3 hours for each day. In general, the number of days in which the indoor air temperature exceeding the upper thermal comfort limits during the survey months was 9 occurrences.

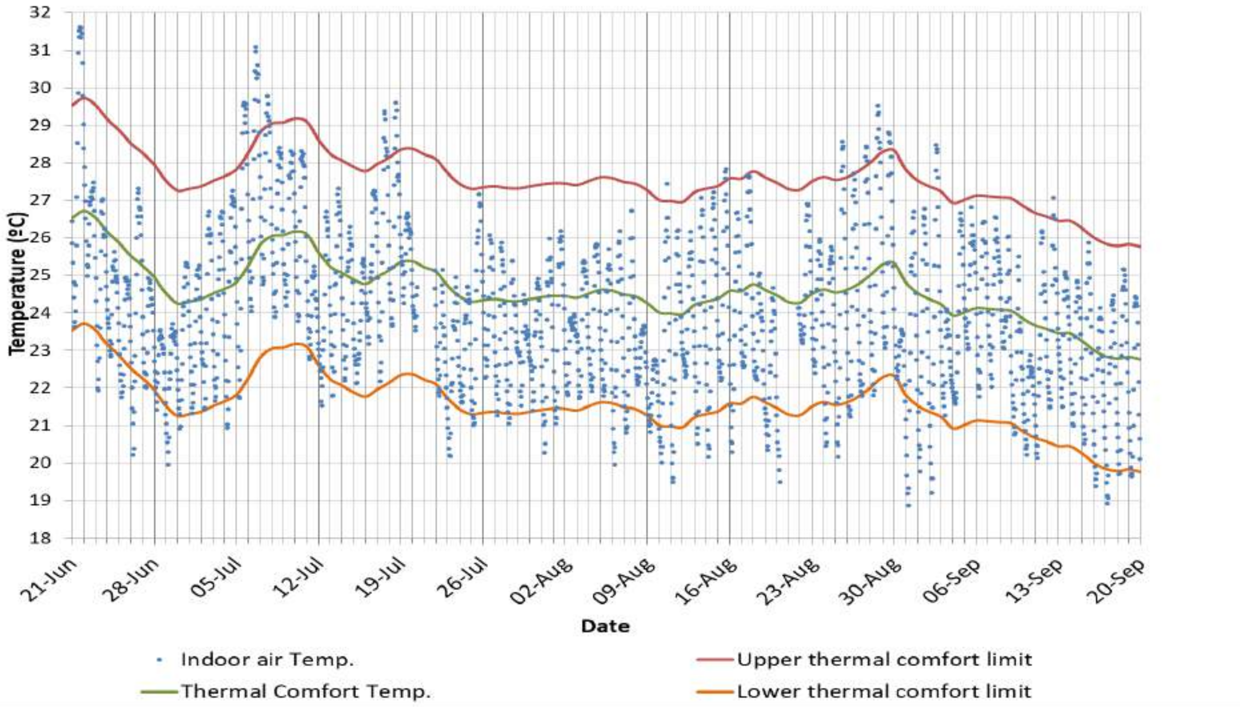


Figure 8. Hourly internal measured temperature during occupant hours (9:00-20:00) weekdays and the thermal comfort temperature with both upper and lower limits.

4.2. Spot detailed measurement results

The acquisition of thermal-hygrometric parameters defined by BS EN ISO 7730 (BSI 2005), BS EN ISO 10551 and ASHRAE standard 55 (Ashrae 2010) was the base for the measurement methodology to evaluate comfort at specific points within the occupied zone in the studying large space using PMV and PPD indices to consider air speed and direction and relative humidity. This is because low air speed was measured in the office which has an impact on thermal comfort as will be discussed in section 4.3. The measured values of the thermal comfort parameters are tabulated in Table 4 for several days during summer 2016 and summer 2017.

Table 4. Synthesis of measured data for several days during summer 2016 and 2017

Date	Height (m)	Mean air temp. (℃)	Mean air speed (m/s)	RH (%)	Metabolic rate (met)	Clothing insulation (clo)	PMV	PPD (%)
5/9/2016	1.2	24.3	0.18	67.6	1.2	0.5	-0.18	6
7/9/2016	1.2	25.7	0.19	51.1	1.2	0.5	+0.07	5
9/9/2016	1.2	25.0	0.2	55.9	1.2	0.5	-0.12	5
31/8/2017	1.2	26.2	0.03	45.1	1.2	0.5	+0.46	9
5/9/2017	1.2	26.1	0.03	56.5	1.2	0.5	+0.50	11
11/9/2017	0.1	25.7	0.02	42.9	1.2	0.5	+0.3	7.0
	1.2	26.0	0.04	42.9				
	1.8	26.2	0.0	42.5				

The PMV was calculated using a spreadsheet based on the algorithm given in ISO 7730 standard (BSI 2005) . The result of PMV values were near to zero or lower in the summer of 2016 while the values were higher than zero for all the three days in summer 2017. In fact, all of the PMV values were in the recommended internal range by ISO 7730 which is -0.5+ 0.5. Note that the temperature was within adaptive thermal comfort limits as calculated and shown in Figure 7. Moreover, PPD is the predicted percentage of dissatisfied and calculated in accordance with PMV index; its values were in the suggested range between 0 to 15 percent (ISO 7730) for both summer 2016 and 2017 days. Also, the relative humidity in the office was generally within the comfort limits, ranging from 51% to 67% and from 42% to 44% for summer of 2017. Furthermore, in 11/9/2017 the air temperature at height 1.8m (head level) is higher than that at 0.1m (foot level) with a mean vertical temperature difference was 0.5 ℃. If this difference was 3 ℃ or more, warm discomfort could be perceived at the head, and cold discomfort can be felt at the feet, while the occupant is thermally neutral as a whole. In addition to that, there was no draft at any day due to significantly low air velocities which were near to zero particularly for summer of 2017. Both air draft and vertical temperature difference are the main reasons for causing local discomfort (ASHRAE 2010)(Fathollahzadeh et al. 2016).

4.3. Questionnaire survey results

A total amount of 50 questionnaires were collected during three days and processed. Table 5 shows the results of the questionnaires analysis,

Table 5 Questionnaires numbers, date and analysis: synthesis of main results

Date	Number of questionnaires	MPV_q	TDI (%)	TPI (%)	UAMI (%)
31/8/2017	14	0.25	28	0	50
5/9/2017	16	0.8	19	19	63
11/9/2017	20	0.25	15	5	60

For the first day 31/8/2017 the actual mean vote PMV_q was found to be slightly warm (i.e. 0.25) where about half of the people were dissatisfied with air movement. Similarly, the PMV_q for day 5/9/2017 was 0.8 which appeared to be slightly warm and a very low air movement were observed which makes 63% of the office occupants' discomfort. Consequently the thermal dissatisfaction index (TDI) was 19% in that day. In the same way, the questionnaires data for 11/9/2017 revealed a thermal sensation oriented towards hot where PMV_q value was 0.25 in the office that day. About 5% (TPI) of people preferred to feel cooler than it was since 15% (TDI) of them felt thermally dissatisfy. The low movement of air makes the discomfort of occupants worse where 60% (UAMI) of occupants were dissatisfied about the air movements. It might be concluded that the office represented a higher percentage of dissatisfied. This is possibly due to very low air velocity inside the enclosure.

Figure 9 shows the subjective responses to temperature for the three days. Seven of the response for days 31/8/2017 and 11/9/2017 claimed that the temperature in the office is neither hot nor cold but only three for day 5/9/2017. More votes for slightly warm and warm were on 5/9/2017 compared to the other two days. It is observed that no votes from any occupants in any days are between the warm and hot regions.

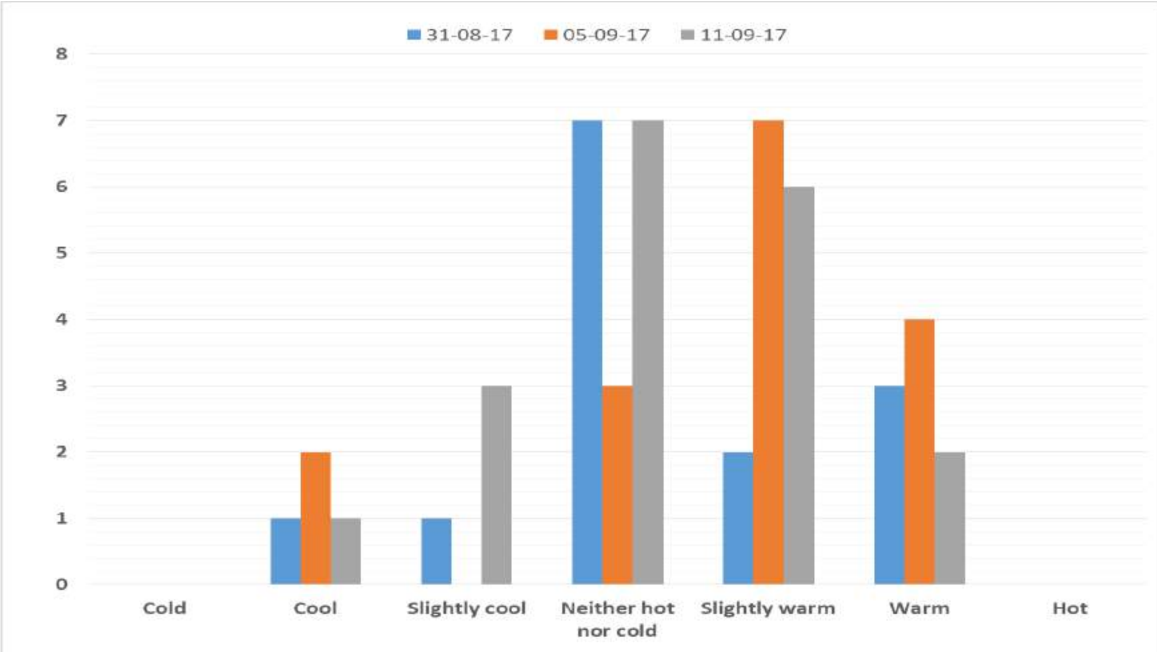


Figure 9. Distribution of subjective response to temperature for three days

Figure 10 shows that the subjective responses to humidity biased towards neutral category. More people in day 5/9 perceived that the air was slightly humid or humid than in days 31/8/2017 and 11/9/2017. No respondent perceived the air as very humid in any of the days.

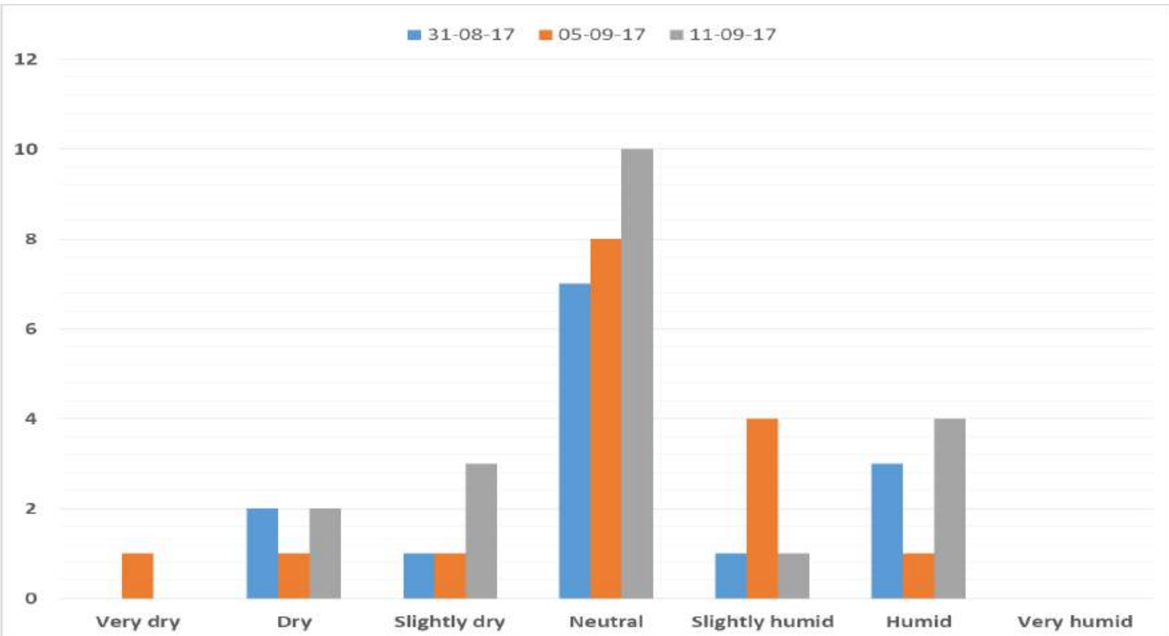


Figure 10. Distribution of subjective response to humidity for three days

The distribution of occupants' responses to the air movement was considerably biased towards the scale presenting the overall feeling of the air being motionless, see Figure 11. More than half of the respondents in each day claimed that the air in the office was slightly still, still or very still. Several reported that air movement was acceptable. It was observed that one occupant claimed that the air was slightly draughty but no votes for draughty and very draughty.

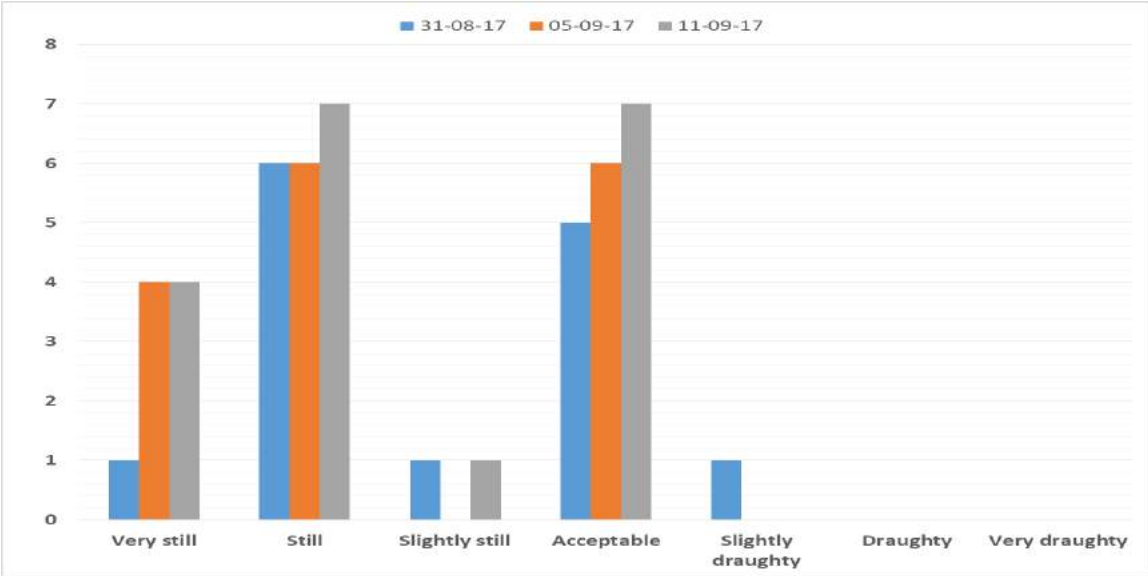


Figure 11. Distribution of subjective response to air movement for three days

Figure 12 shows the distribution of votes of the overall thermal comfort for the three days where the distribution skewed towered the comfortable and slightly comfortable regions. Only four in 31/8/2017, three in 5/9/2017 and one in 11/9/2017 voted the office were uncomfortable.

.

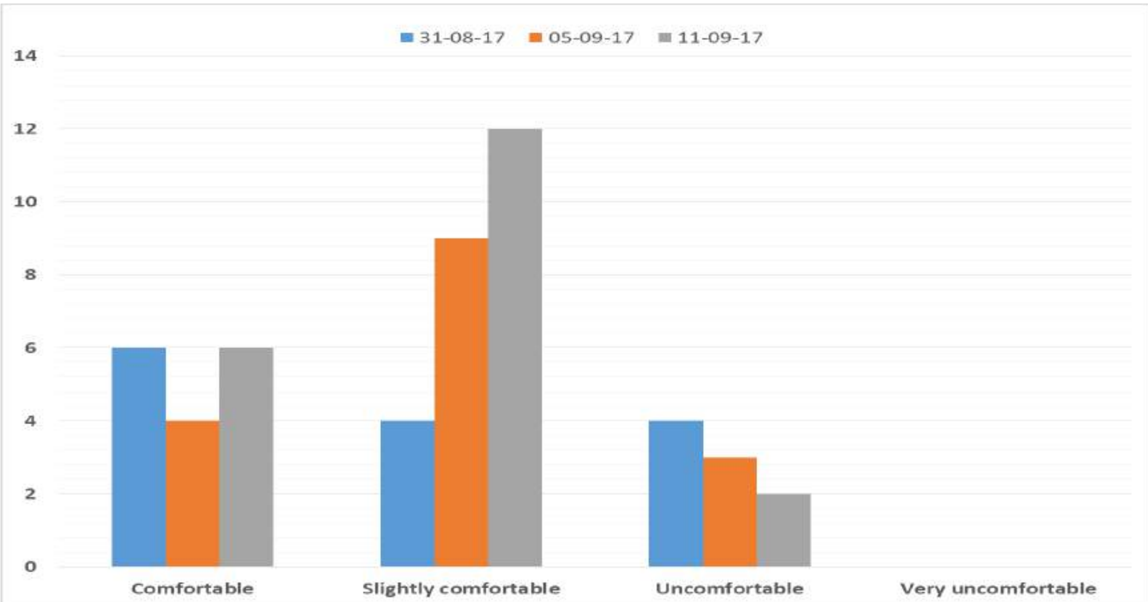


Figure 6. Distribution of subjective response to overall comfort for three days

5. Discussion

In this paper, three different tools have been used to evaluate the thermal comfort of a mechanically ventilated large space. The first was based on data from the long-term monitoring survey of air temperature and the correlation of of the indoor air temperature with outdoor temperature was calculated for the summer of 2016 (Figure 4) and the summer of 2017 (Figure 5). It was observed that both results are comparable with correlations using similar analysis. Nicol (2017) points out that typically for FR buildings the regression slope is between 0.5 and 0.6 between indoor operative temperature and outdoor air temperature which is similar to the regression slopes for both summers 2016 and 2017. Accordingly, the researchers' office can be treated as FR building although it has a mechanical ventilation system. Looking at the range of indoor temperature and outdoor temperature (Figure 3), this remained stable at 6-7 K throughout the day. CIBSE TM50 (CIBSE 2013) table 2 suggested that the acceptable temperature range for a new or renovation free-running building is ± 3K; from Figure 7 nine occurrences in which the indoor air temperature exceeded the upper thermal comfort limits in summer 2017.The second tool used in this paper was short term detailed measurements to include air speed at different heights in the occupied zone. The comfort temperature for occupants is assumed to be most satisfied when both PMV and PPD are closed to minimum values. Therefore, the calculated PMV and PPD values for the assigned days were in the recommended range by ISO 7730. The last tool was a questionnaire survey in which the occupants reported that the office was generally neutral. However, a high percentage of them claimed that the air movement was not acceptable in all the assessed days during the summer of 2017. Teli et al. (2016) mentions that people do not have the same metabolism, cultures and familiarity with available adaptive opportunities for particular heating or cooling systems.

6. Conclusion

This paper presented results from three tools used to evaluate the thermal comfort of a large space office building. The comparisons between the measurement (analysed using PMV/PPD and adaptive thermal comfort principles) and the questionnaire surveys' results show good agreement between predictions and occupant evaluation. The existing ventilation system was able to meet the requirement for thermal comfort in this large enclosure for most of the time in terms of temperature and humidity. However, with regards to the air movement, this did not achieve the recommended and desired levels and this has been indicated by the occupants during the survey. Therefore, the type of ventilation system, and in particular the configuration and position of inlets, is very important for providing comfort without excessive heating or cooling to compensate for air movement deficiencies. Based on these results, our work will continue to investigate impinging and confluent jet systems using CFD modelling to examine their effectiveness in improving internal conditions within the occupied zone of large spaces with minimum of energy use.

7. References

Ashrae, 2010. ANSI/ASHRAE 55-2010 : Thermal Environmental Conditions for Human Occupancy. *ASHRAE*, p.30.

Awbi, H., 2003. *Ventilation of buildings*, Available

BSI, 2007. BS EN 15251: 2007: Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality , thermal environment , lighting and acoustics Contents. , 3(BS EN 15251), pp.1–50.

BSI, 2005. BS EN ISO 7730: 2005: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. *Management*, 3, pp.605–615.

Buratti, C. & Ricciardi, P., 2009. Adaptive analysis of thermal comfort in university classrooms: Correlation between experimental data and mathematical models. *Building and Environment*, 44(4), pp.674–687.

Calay, R.., Borresen, B.. & Holdø, A.., 2000. Selective ventilation in large enclosures. *Energy and Buildings*, 32(3), pp.281–289.

CIBSE, 2013. The limits of thermal comfort : avoiding overheating in European buildings. *CIBSE Tm52*, pp.1–25.

Fathollahzadeh, M.H., Heidarinejad, G. & Pasdarshahri, H., 2016. Producing a better performance for the under floor air distribution system in a dense occupancy space. *Energy and Buildings*, 126, pp.230–238.

Heiselberg, P., Murakami, S. & Roulet, C., 1998. Ventilation of large spaces in buildings. *Final Report IEA Annex*.

HOBO, Onset HOBO and InTemp Data Loggers.

Humphreys, M.A., Rijal, H.B. & Nicol, J.F., 2013. Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. *Building and Environment*, 63, pp.40–55.

International Energy Agency (IEA), 1998. IEA Annex 26: Energy Efficient Ventilation of Large Enclosures - Technical Synthesis Report.

Li, Q. et al., 2009. CFD study of the thermal environment in an air-conditioned train station building. *Building and Environment*, 44(7), pp.1452–1465.

Mateus, N.M. & Carrilho da Graça, G., 2017. Simulated and measured performance of displacement ventilation systems in large rooms. *Building and Environment*, 114, pp.470–482.

Nicol, F., 2017. Temperature and adaptive comfort in heated, cooled and free-running dwellings. *Building Research and Information*, 45(7), pp.730–744.

Ricciardi, P. & Buratti, C., 2015. Thermal comfort in the Fraschini theatre (Pavia, Italy): Correlation between data from questionnaires, measurements, and mathematical model. *Energy and Buildings*, 99, pp.243–252.

Ricciardi, P., Ziletti, A. & Buratti, C., 2016. Evaluation of thermal comfort in an historical Italian opera theatre by the calculation of the neutral comfort temperature. *Building and Environment*, 102, pp.116–127.

Teli, D. et al., 2016. Thermal adaptation to high indoor temperatures during winter in two UK social housing tower blocks. *Windsor 2016*, (April), pp.7–10.

Zhao, X., Yu, W. & Tan, D., 2017. Thermal Comfort Study Based on Questionnaire Survey among Occupants in Different Climate Zones in China. *International Journal of Environmental Science and Development*, 8(6), pp.430–434.

WORKSHOP 6

Domestic Comfort and Health at Low temperatures

Invited Chairs:
Lyrian Daniel and Dennis Loveday

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Residential wintertime comfort in a temperate Australian climate

Lyrian Daniel, Emma Baker and Terence Williamson

Healthy Cities Research Group, School of Architecture & Built Environment, The University of Adelaide, Adelaide, Australia; lyrian.daniel@adelaide.edu.au, emma.baker@adelaide.edu.au, terence.williamson@adelaide.edu.au

Abstract: There is a growing realisation among policy-makers and researchers that Australia has a vastly under-recognised cold housing phenomenon. Overshadowed by the dominance of concern for summer heatwaves and cooling, to date little Australian work has been undertaken on winter housing conditions. In responding to this research and evidence gap, this paper presents the findings from a wintertime thermal comfort field study in metropolitan Adelaide, South Australia between July and October 2017. Participant households were selected from a larger random sample of 4,500 Australian households in the Australian Housing Conditions Dataset (AHCD). Data for this field study was collected from 19 households in the AHCD who self-identified as unable to keep warm in cold weather in their homes. On average, internal temperatures in the sample dwellings were well below standard thermal comfort levels. Interestingly, findings also indicate that residents reported being comfortable at temperatures much lower than accepted norms. Overall however, they reported very low satisfaction with their indoor thermal environment. Several hypotheses are put forward as possible explanations of these findings but will need to be subject to further research. Nevertheless, the findings from this paper position indoor cold as a forefront concern for Australian housing research and policy development.

Keywords: Cold housing; thermal comfort; adaptive model; heating.

1. Introduction

While widely regarded as a sunburnt country, an emerging body of research suggests that Australia has a vastly under-recognised cold housing problem. Cold housing, its causes, and effects have been well researched overseas, but in Australia, residential building performance research is almost exclusively focused on adaption and resilience to warm temperatures and extreme heat events. A combination of relatively poor minimum thermal performance standards for residential buildings, a high proportion of heating degree day dominated climates, and some of the highest energy prices in the world means that many Australian households experience cold indoor conditions during winter and transitional seasons.

The international literature documents clear (direct and indirect) effects of cold indoor conditions on human health and wellbeing (for example Howden Chapman et al., 2007; Wang et al., 2017), and securing warm houses are is regarded as a critical health intervention in many countries (Marmott & Bell, 2008; Thomson et al., 2009; Curl & Kearns, 2017). This is reinforced by the World Health Organization’s (WHO) prioritisation of guidelines for low indoor temperatures, following substantial international evidence on the role of indoor cold conditions on the seasonal ill-health and mortality (for example Howden-Chapman et al., 2017).

In addition to the problem of cold housing being under acknowledged in the Australian context, high power prices in combination with poor cold weather building performance are also likely to exacerbate any health effects. This paper reports on a new study of temperature conditions and winter comfort in a small sample of houses. It is the first stage in building an essential larger national winter housing conditions evidence base. It explores householder temperature preferences and whether (and how) residents are able to achieve winter warmth and comfort.

In a small sample of homes, self-identified as having difficulty keeping warm during winter, the paper will address two key research questions:

RQ1: What are the thermal comfort conditions within the sample houses?

RQ2: Do the prevailing indoor thermal conditions meet acceptable minimum standards?

2. Methods

A longitudinal thermal comfort survey was conducted from July to October 2017 with 19 participating households in metropolitan Adelaide, South Australia.

Adelaide has a warm-temperate climate and a Köppen climate classification of 'Csb' or 'warm-summer Mediterranean'. It has four typical seasons with summer from December to February and winter from June to August. January and February are historically the hottest months, although heatwaves are also regularly experienced during March, while June and July are the coolest. The majority of annual rainfall (~550mm) is received between late autumn and early spring (May through to September).

The sample for this study was drawn from a large (4,500 households) random sample of Australian households that responded to a broader survey on housing conditions in 2016 (https://architecture.adelaide.edu.au/AHCD/). All eligible households resided in metropolitan Adelaide and who, having self-identified in the 2016 study as having difficulty keeping warm during winter, had agreed to participate in further research. A total of 70 households met these criteria. Each was sent an approach letter and project information, and were then followed up by telephone during June/July 2017. Nineteen households agreed to participate. Figure 1 shows the locations of the participating households in relation to the local Bureau of Meteorology (BOM) weather monitoring stations, and their relatively even geographical distribution across the metropolitan area.

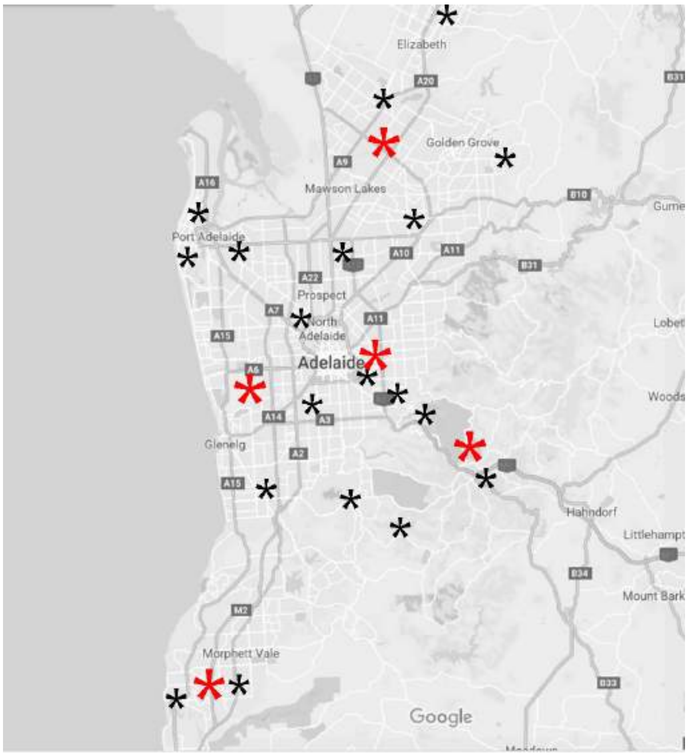
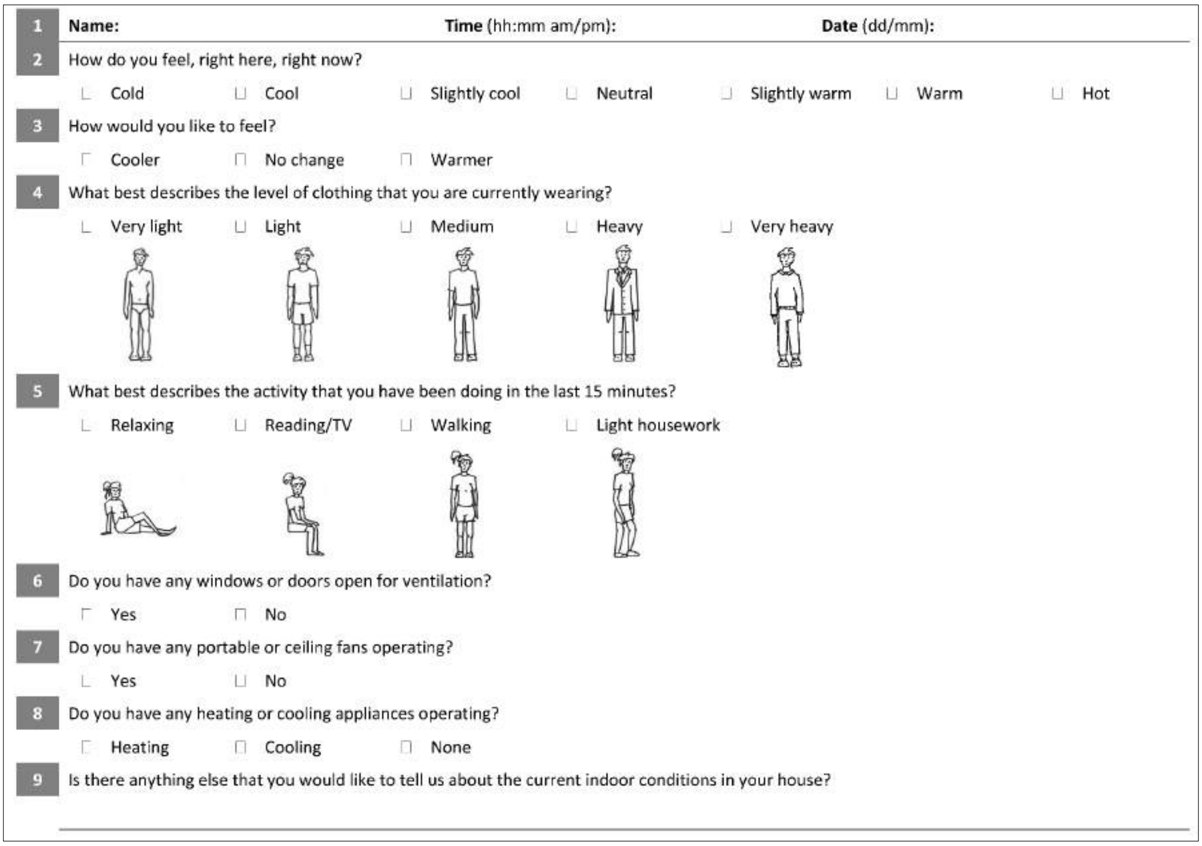


Figure 1: Locations of sample houses relative to primary metropolitan weather stations (Source: Google Maps, 2018)

For each participant household, an extended commencement interview was conducted detailing heating and cooling conditions, energy usage, housing and tenure conditions, and socioeconomic descriptors. Data loggers were placed in living rooms and bedrooms from July 2017. HOBO U12-013 data loggers recorded air temperature (±0.35 °C) and relative humidity (±2.5%) at 15-minute intervals, all loggers had been calibrated in a previous deployment 12-months prior to this fieldwork. The loggers were generally located in the middle of the room/building (i.e. away from external walls/windows) away from heat sources and direct solar radiation, and at around sitting/standing height.

All householders over the age of 18 were also asked to complete a once daily paper-based thermal comfort survey which included the seven-point ASHRAE sensation scale, the three-point McIntyre preference scale as well as descriptions of their clothing arrangement, recent physical activity and operation of windows, fans, heating and cooling (Figure 2). The date and time of the vote was also recorded.

The surveys were manually matched to the corresponding environmental data recorded from the logger, as well as coincident outdoor temperature, daily average outdoor temperate, and running weighted daily mean temperature (based on the ASHRAE 55-2013 equation). Weather data were sourced via the BOM Climate Data service for station numbers: 023090 - Adelaide (Kent Town), 023034 – Adelaide Airport, 023842 – Mt Lofty, 023013 Parafield Airport and 023885 – Noarlunga. Analyses were completed in Microsoft Excel and IBM SPSS.


1 **Name:** **Time** (hh:mm am/pm): **Date** (dd/mm):

2 How do you feel, right here, right now?

☐ Cold ☐ Cool ☐ Slightly cool ☐ Neutral ☐ Slightly warm ☐ Warm ☐ Hot

3 How would you like to feel?

☐ Cooler ☐ No change ☐ Warmer

4 What best describes the level of clothing that you are currently wearing?

☐ Very light ☐ Light ☐ Medium ☐ Heavy ☐ Very heavy

5 What best describes the activity that you have been doing in the last 15 minutes?

☐ Relaxing ☐ Reading/TV ☐ Walking ☐ Light housework

6 Do you have any windows or doors open for ventilation?

☐ Yes ☐ No

7 Do you have any portable or ceiling fans operating?

☐ Yes ☐ No

8 Do you have any heating or cooling appliances operating?

☐ Heating ☐ Cooling ☐ None

9 Is there anything else that you would like to tell us about the current indoor conditions in your house?

Figure 2: Thermal comfort vote survey form

3. Results

3.1. Weather

The study period covered the last two months of winter (July and August) and the first two months of spring (September and October). While there was some variation, the weather conditions are largely typical of historical weather patterns in Adelaide during this time of year (see Table 1). For example, the monthly mean of daily maximums and minimums for July and October were slightly warmer than average, for August slightly cooler and about average for September. July was slightly less humid than the historical average while the other months were relatively stable. Both July and August received more rainfall than average, and September and October received slightly less.

Figure 3 shows the mean daily temperature for the five closest weather stations to the sample dwellings. The majority of houses were located on the Adelaide plains (i.e. weather represented by recordings at the Adelaide, Adelaide Airport, Parafield Airport and Noarlunga weather stations), three were located in the Adelaide Hills (Mt Lofty weather station) where the daily mean temperature was, on average, 4.8 °C cooler than Adelaide for the study period.

Table 1: Comparison of historical temperature, humidity and rainfall averages with those of July to October 2017 (Source: Bureau of Meteorology, 2018, Station number 023090)

Variable	Year	July	August	September	October
Mean maximum temperature (°C)	1977-2017	15.3	16.7	19.1	22.1
	2017	16.4	15.9	19.4	24.3
Mean minimum temperature (°C)	1977-2017	7.6	8.1	9.8	11.5
	2017	8.1	7.9	10.7	12.3
Mean relative humidity (%)	1977-2017	69.0	62.5	56.5	50.0
	2017	64.5	62.0	55.0	51.5
Mean rainfall (mm)	1977-2017	77.7	67.8	59.6	41.9
	2017	91.2	87.8	56.0	36.8

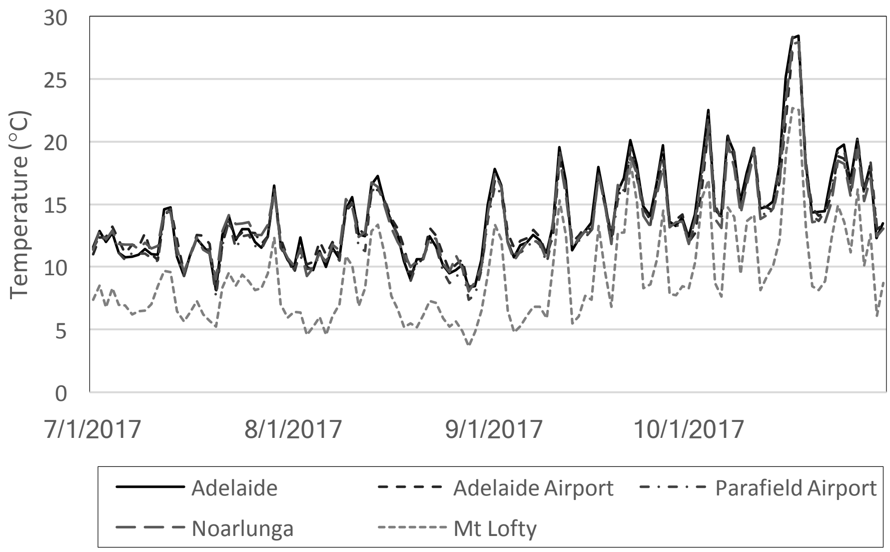


Figure 3: Daily mean temperature at five metropolitan weather stations July to October 2017 (Source: Bureau of Meteorology, 2017)

3.2. Household & dwelling characteristics

The houses were typical of those found in suburban Adelaide. The mean age of the dwellings was 63.9 years (SD 29.9), ranging from 30 to 138 years old. Eleven houses had tiled roofs, seven had metal sheet roofs and one had an asbestos shingle roof. Most (16) had masonry external walls (primarily double brick or brick veneer), two had fibro cement sheet external cladding and one had asbestos cladding.

Nine households owned their homes outright, six with a mortgage, two rented from a private landlord and two rented from the State Housing Authority (social housing). Reflecting broader Australia trends, the majority (16) of properties were separate houses while three were semi-detached (e.g. single storey unit or townhouse). Similarly, most (16) were single storey, only three were double storey houses.

Table 2 provides a summary of the key socio-demographic characteristics of household responding persons. Overall, it shows the sample population to be largely concentred in the older age cohorts, with low to moderate incomes. More than half of all households lived alone or in a couple. Interview data (not shown) also reveals that a number in the sample population had age and non-age related disabilities and health problems.

Table 2: Household demographic variables, age and gender by household responding person

Variable	**Count**
Age	
1=18 to 24 years	0
2=25 to 34 years	0
3=35 to 44 years	1
4=45 to 54 years	3
5=55 to 64 years	8
6=65 to 74 years	5
7=75 years or over	2
Gender	
Male	8
Female	11
Income	
Up to $12,000	1
$12,001 - $20,000	2
$20,001 - $40,000	3
$40,001 - $60,000	5
$60,001 - $80,000	1
$80,001 - $100,000	1
$100,001 - $150,000	3
$150,001 - $200,000	0
More than $200,000	0
Not stated	3
Household structure	
Couple with no children	4
Couple with children	2
One parent family with children	3
Lone person	7
Other family structure	2
Shared living arrangement with friends	1

During the commencement interview participants were asked if they had any plans to make changes to their dwelling to improve wintertime conditions. Seven of the 19 households planned to make changes, including building sealing (3), installation of double glazing (3) and upgrading their main heating appliance (3). For five of the 12 households that had no plans, improving the thermal performance of their dwelling was not a priority, three were constrained by tenure (rental property or subject to other legal constraints), two were constrained by lack of financial resources and two were unsure of what could be done. Five of the households that had no plans to improve dwelling thermal performance cited the cold nature of their dwelling as a source of dissatisfaction in the original 2016 survey.

3.3. Thermal comfort

A summary of logger and survey data from the dwellings is shown in Table 3. The average indoor temperature at the time a vote was recorded was only 16.9 °C. Indoor relative humidity was very similar to the mean monthly outdoor relative humidity recorded for Adelaide during the study period.

In total, 598 comfort surveys completed from July to October (Table 3). Analysis of the comfort survey data shows that the mean of the thermal sensation votes recorded by the occupants is -0.6, indicating predominantly cooler than neutral thermal sensation. The mean of the thermal preference votes is 2.5 indicating overall preference to be warmer. This is supported by the cross-tabulation of the thermal sensation and preference votes (Table 4), where a high proportion (38.0%) of the votes recorded a thermal sensation cooler than neutral, and preference to be warmer. While a relatively small proportion (18.9%) of votes recorded a thermal sensation warmer than neutral, very few indicated a preference to be cooler (<1%). Only 66.1% of votes recorded acceptable conditions denoted by TSV=±1.5.

The average of the response to clothing arrangement is 3.4 (on the scale of 1-5), corresponding to medium to heavy clothing insulation (assumed to be 0.72-1.0clo). Preliminary comparison of the clothing response data with indoor temperature showed little adaption of clothing arrangement throughout the period of the study (results not shown).

Table 3: Thermal comfort survey and environmental measurements July to October 2017, summary statistics

Variable	**N (missing)**	**Minimum**	**Maximum**	**Mean**	**Standard deviation**
Indoor temperature (°C)	598	10.0	28.5	16.9	3.2
Average daily indoor temperature (°C)	598	11.3	24.1	16.5	2.6
Relative humidity (%)	598	39.1	88.2	60.6	8.6
Outdoor temperature (°C)	598	2.6	30.9	12.9	4.8
Average daily outdoor temperature (°C)	598	3.7	25.1	12.2	3.7
Running weighted mean outdoor temperature (°C)	598	4.8	18.2	12.1	3.0
Thermal sensation vote (TSV) (-3-+3)	595(3)	-3	3	-0.6	1.4
Thermal preference vote (TPV) (1-3)	568(29)	1	3	2.5	0.5
Clothing arrangement response (1-5)	595(3)	1	5	3.4	0.6
Activity level response (1-4)	576(22)	1	4	2.5	1.0
	N (missing)	**Frequency (count)**			
Windows & (external) doors	597(1)	Open		197	
		Closed		400	
Fans	597(1)	On		42	
		Off		555	
Heating & Cooling	595(3)	Heating on		238	
		Cooling on		1	
		None		356	

Within the sample dwellings, heating was recorded as operating for 40.0% (238) of instances when surveys were completed. Notably though, a number of participants reported never using the heating because they were unable to afford energy costs. There were 356 surveys completed at times when the house was free-running (no heating or cooling appliances operating), one instance of air-conditioning and one instance where this information was not recorded. Windows and external doors were open in just over a third of all cases. While normally this would be interpreted as the desire for passive cooling, the researchers observed a number of houses where windows were continually left open a small amount for fresh air even while heating was on. This is supported in the data – there were 77 instances where participants reported both open windows and heating within the same room. The use of fans was more seldom reported (7.0% of surveys), of these cases 90.5% occurred at the same time as heating was operating and thus seems to have been interpreted as a fan on the heating appliances operating.

Table 4: Cross-tabulation of the proportion of thermal sensation and preference vote responses (%)

	Thermal preference vote			
Thermal sensation vote	**Cooler**	**No change**	**Warmer**	**Total**
Cold	0.0	0.2	12.0	12.2
Cool	0.0	1.6	13.1	14.7
Slightly cool	0.0	5.7	12.9	18.6
Neutral	0.0	26.3	9.4	35.7
Slightly warm	0.2	9.0	2.7	11.8
Warm	0.0	6.4	0.5	6.9
Hot	0.0	0.2	0.0	0.2
Total	0.2	49.3	50.5	100.0

Of 597 comfort votes (acknowledging one warm/humid outlier), 83.4% (497) are below the comfort zone for conditioned spaces (Figure 4). As a proportion of the total number of surveys (597), 64.0% of cases fall outside of the comfort zone and express no preference for change. Remarkably, 76.9% (382) of the votes on the cold side on the comfort zone expressed no preference for change.

The votes cast at conditions within the comfort zone, at relatively warm indoor temperatures (i.e. >20 °C), are primarily from four households. On inspection of these four households, several possible explanations for the warmer conditions could be advanced but would need further testing:

- The first house had a particularly high occupancy rate (four children and three adults) but was quite modest in size, resulting in high incidental heat gains from occupants and electronic entertainment equipment);
- The second were the eldest household whose primary living area had expansive western facing glazing that received large amounts of solar radiation in the afternoon;
- The third ran a commercial catering business – the kitchen was situated in the same open-plan living area in which the logger was located; and
- The final household (including three young children) were recent immigrants from the UK, and more used to stable and higher indoor temperature than currently experienced – their heating practices, with timer-controlled gas space heating, attempted to replicate the function of central heating.

What is clear from these observations is that the relationship between thermal sensation and behaviour, and indoor conditions (e.g. feeling cold – turning heating on –

increase in indoor temperature) is likely to be mediated to a large extent by a range of other factors including demographic/household (health, occupancy, lifestyle), building (orientation, design) as well as thermal experience (history), which could be tested in a comprehensive study.

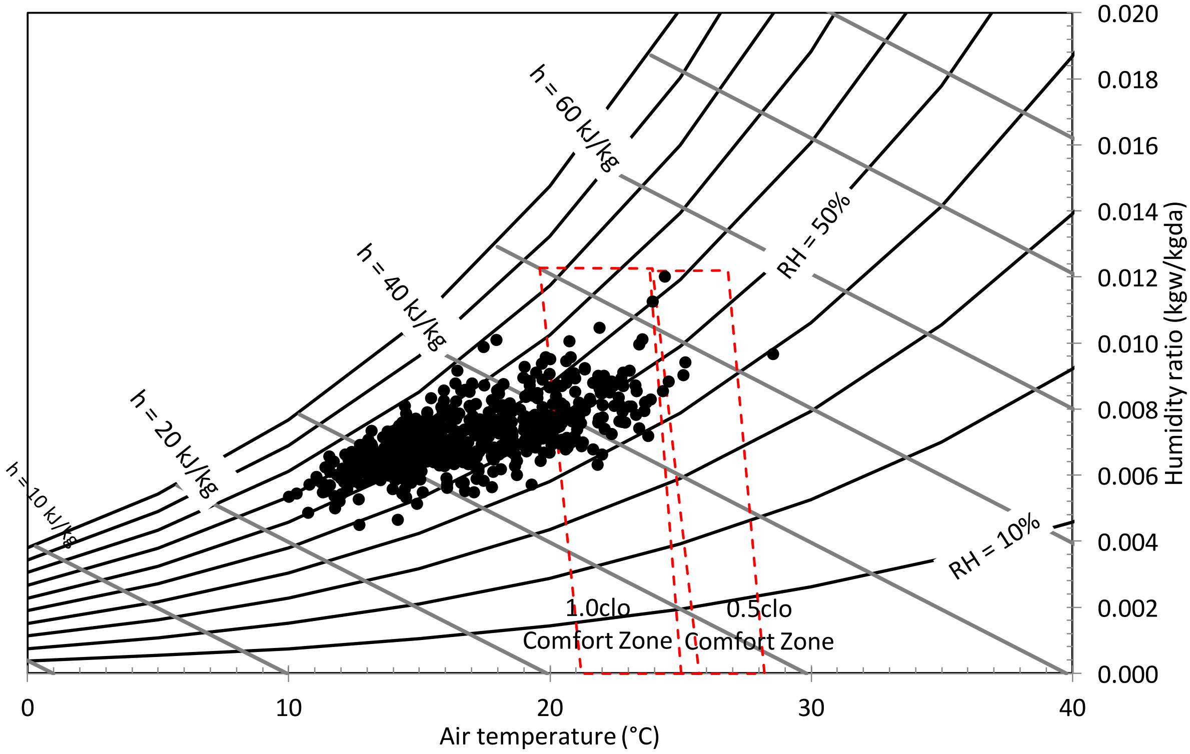


Figure 4: Indoor environmental conditions at the times that thermal comfort vote surveys were completed compared with the ASHRAE Standard 55-2013 acceptable comfort zone for conditioned spaces

Thermal sensitivity

Central to understanding a cohort's perception of thermal conditions is the relationship between subjective 'right-here-right-now' thermal sensation vote and indoor temperature. For all the 19 households combined, Figure 5 shows the weighted regression of the mean TSV on the indoor temperature binned in 0.5K intervals (R^2=0.56, p<0.01). The indoor temperature corresponding to a 'neutral' (TSV=0) vote is 22.6 °C.

The slope of this regression can be interpreted as the cohort's relative thermal sensitivity, i.e. a flatter slope indicates the cohort are less likely to change their thermal sensation vote with changing temperature. For this cohort, a temperature change of 10.2K accounts for one-unit change of the TSV scale. Relative to other broadly comparable studies, this cohort is 55% less sensitive to indoor temperature variation than those in an historical sample of 20 houses in Adelaide (0.22) (Williamson et al. 1989) and 30% less sensitive than a recent sample of 20 houses in Melbourne (0.14) (Daniel et al. 2016)[1].

One possible explanation of the relative lack of sensitivity of this cohort could be attributed to a factor of forgiveness (e.g. as per the approach of Deuble & de Dear, 2014) or

[1] Studies by Williamson et al. (1989) and Daniel et al. (2016) were carried out over an entire year, thus representative of both summer and winter conditions, which may factor in thermal sensitivity. Values reported for these studies are from unweighted regression analyses.

perhaps more accurately framed here as a 'resignation factor' (as described in Pearlin & Schooler, 1978), where subjects are resigned to conditions which they find difficult or impossible to change, e.g. because of constraints in capacity to pay for heating energy or ability to upgrade the building envelope. This will be tested in future work.

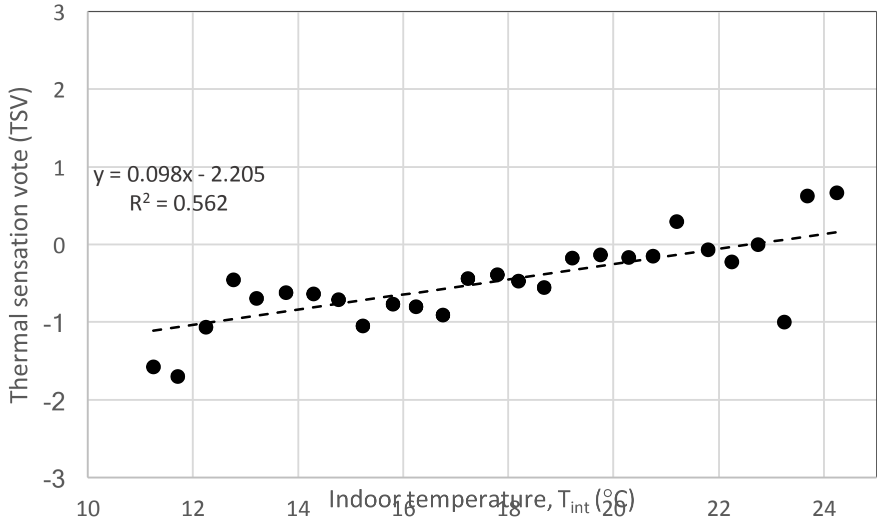


Figure 5: Weighted regression of thermal sensation vote and indoor temperature binned in 0.5K intervals

Thermal acceptability

Congruent with the interpretation of Figure 6, regression of the proportion of 'acceptable' TSVs (TSV=±1.5) on indoor temperature demonstrates a low level of satisfaction (Figure 7). Based on a weighted curve estimate, maximum acceptability is 78%, which corresponds to an indoor temperature of 22.8 °C. Studies of Australian samples in coastal-temperate and hot-humid climates have reported maximum acceptability of ~90% (Kim et al. 2016) and ~95% (Williamson & Daniel, 2018). This relatively low level of acceptability suggests that factors other than temperature are likely to cause thermal dissatisfaction amongst this cohort.

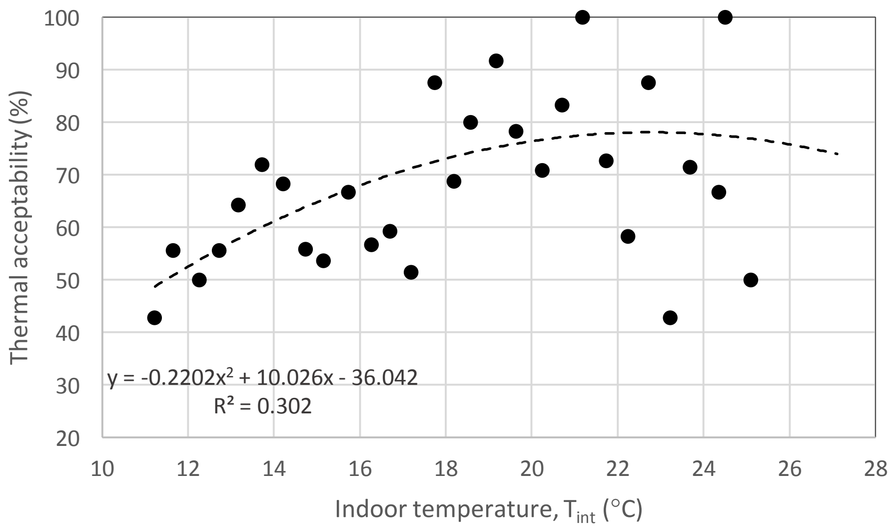


Figure 6: Weighted quadratic regression of proportion of acceptable thermal sensation votes and indoor temperature binned in 0.5K intervals

Adaptive relationship

The relationship between indoor temperature when respondents judge conditions to be acceptable (i.e. TSV=±1.5) and prevailing mean outdoor temperature is given in Figure 7. The data tend toward the lower limits of the ASHRAE Standard 55-2013 Adaptive Comfort Model with a majority (65.2%) of cases falling below the 80% lower acceptability limit (assumed to continue below 10 °C for this analysis). This demonstrates that the conditions that this cohort judge to be acceptable are considerably cooler that those described as acceptable by the adaptive model.

The slope of the adaptive relationship (0.46) represented in Figure 7 appears to demonstrate lesser coupling between indoor and outdoor conditions relative to results from studies of residential comfort in broadly comparable climates. For example, the slope derived for a sample of Chinese houses in a 'hot-summer, warm-winter' climate is 0.55 (Yan & Yang, 2017), while for a sample of Australian houses in a cool-temperate climate, it is 0.62 (Daniel et al. 2015). Both of these studies aggregate data across heating and cooling seasons. Honjo and colleagues (2012) present the adaptive relationship for data disaggregated into heating, cooling and natural ventilated cases for a sample of Japanese houses in a warm-temperate climate. The slope of the adaptive relationship for naturally ventilated cases (0.53) is similar to the two initial comparisons, however it is considerably lower for the heating cases (0.30) (Honjo et al. 2012). The variation in this relationship between different samples under similar climatic conditions could be hypothesised as different cultural practices around the operation and arrangement of the dwelling for 'comfort' conditions but this would need to be tested by further research.

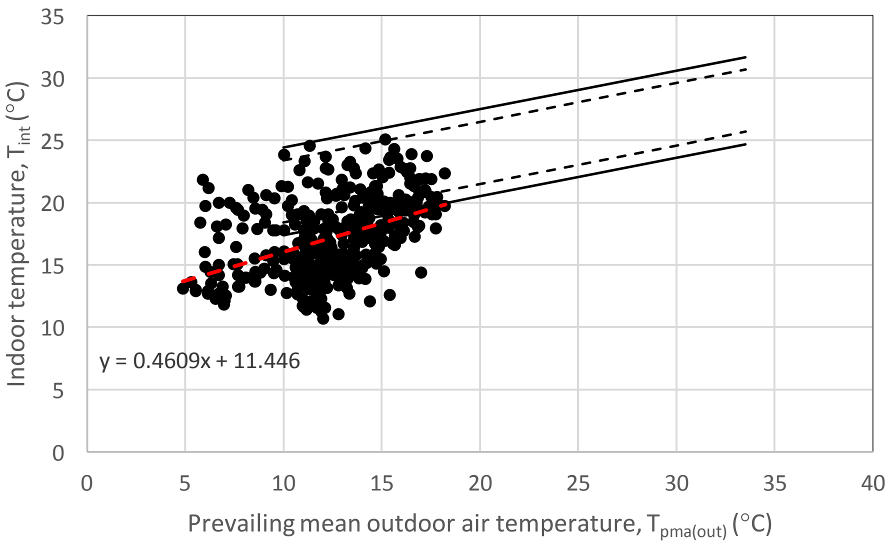


Figure 7: Acceptable indoor temperature (TSV=±1.5) vs. running weighted mean outdoor temperature plotted against the ASHRAE Standard 55-2013 adaptive comfort model 80% and 90% acceptability limits

4. Discussion

Reflecting on the findings described above, this small study suggests a pressing need to understand and measure winter warmth in Australian homes. In addition to these findings, Figure 7 demonstrates that, on average across the 19 dwellings, indoor conditions did not even meet widely held expectations of *minimum* standard conditions (Figure 8). In explaining this deficit we suggest that there are three main causes: dwelling design, construction quality and energy affordability. Importantly, these are all mediated by householders agency (in the light of legal, economic, and social barriers) to act in these three areas. Discussion with householders in the commencement interviews draws into focus a gap between warm housing 'haves' and 'have nots', where for those without, the experience of indoor cold is often one component of a larger bundle of housing insults (Baker et al., 2017), which can be beyond the householders' agency to address. Together with the cohort's low satisfaction with, and sensitivity to, thermal conditions, these findings as a whole add weight to the proposition that, for a range of reasons, the majority of the cohort is resigned to the poor standard of their indoor thermal environment.

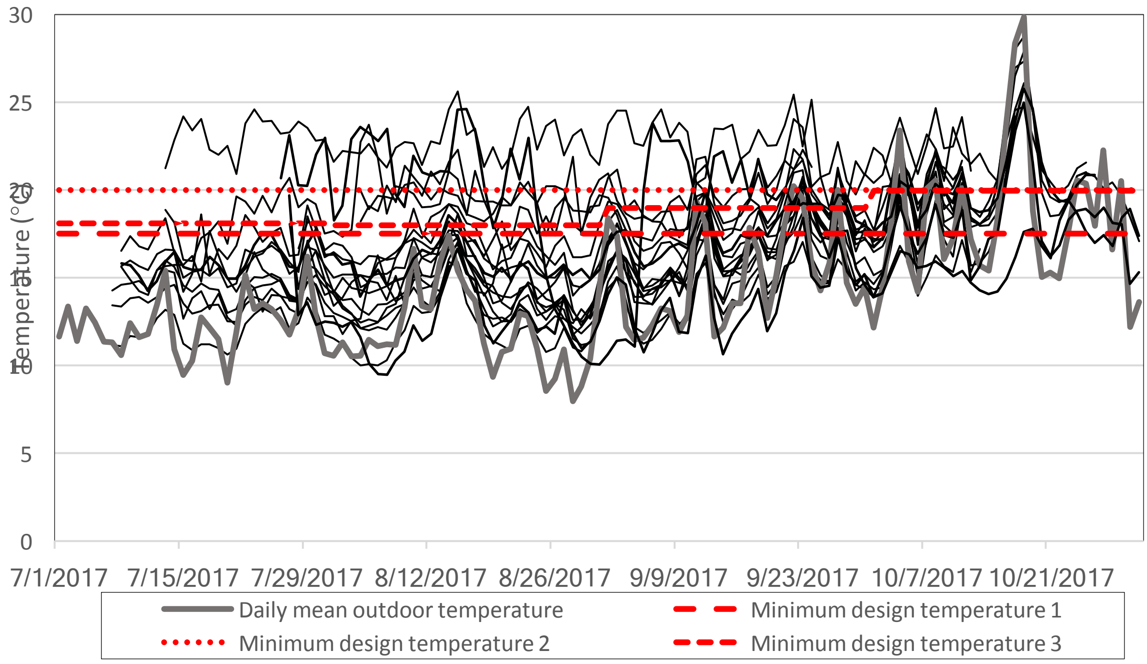


Figure 8. Average daily indoor temperature plotted against a selection of minimum design temperatures[2], July to October 2017

5. Conclusion

This Australian study is particularly interesting in light of recent work suggesting that "*winter mortality is greater in countries with milder climates than in those with more severe winter conditions*" (Howden-Chapman et al., 2017, p4). It points to the issue that winter warmth is dictated, not just by external temperatures, the design of dwellings, their ability to be heated and to retain warmth, but also by the ability of residents to access and afford warm housing. This paper has shown that, in this sample at least, even though external temperatures are far from extreme cold, internal temperatures are lower than would be considered acceptable as indicated by Standards, nor are they satisfactory to the occupants who, for 50.5% of the time, want to be warmer.

[2] Minimum design temperature 1: 17.5°C – 80% lower acceptability limit for houses in Adelaide (Williamson et al. 1989); Minimum design temperature 2: 20°C – heating thermostat setting for living areas during occupied hours (NatHERS, 2012); and Minimum design temperature 3: 18-20°C – adaptive comfort model 80% lower acceptability limits based on monthly mean temperature (ASHRAE, 2013).

The cold homes phenomenon appears real for Australia, though the challenge of responding is hindered by the lack of systematic data of the internal conditions of our housing stock. From this small sample, we can observe considerable heterogeneity in wintertime indoor conditions (Figure 7) and in households' capacity to make thermal improvements to their dwelling. By examining the practices of cold-climate countries that are more universally able to provide warm housing, there are a number of lessons that could be drawn from construction technologies, retro-fit practices, energy subsidy, and bulk-buy schemes.

Beyond the initial challenge of creating baseline evidence on cold houses in warm-climate countries such as Australia, this paper reinforces the need to broaden the motivation for building performance research from its current basis in climate change and energy use, to include the *experience* of people within their homes. Such a shift is important because it then allows us to capture not just the acute impacts of heat (made visible by increasing heatwave events, blackouts and load-shedding) but also the less visible and more chronic human impacts of indoor cold, such as cardiovascular and respiratory ill-health.

6. Acknowledgements

The authors would like to thank the participating households for their time and commitment to the project.

This work was supported by the Australian Research Council (FT140100872 and LE160100056), and the School of Architecture and Built Environment at the University of Adelaide.

Ethical Approval for the project was granted by the University of Adelaide Human Research Ethics Committee (approval number H-2017-094).

7. References

ASHRAE, 2013. *Thermal Environmental Conditions for Human Occupancy, ASHRAE Standard 55–2013*. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Curl, A., & Kearns, A., 2016. Housing improvements, fuel payment difficulties and mental health in deprived communities. *International Journal of Housing Policy*, pp. 1-27.

Daniel, L., Williamson, T., & Soebarto, V., 2016. Neutral, comfort or preferred: what is a relevant model for acceptable thermal environmental conditions for low energy dwellings in Australia? *Proceedings of 9th Windsor Conference: Making Comfort Relevant* 7-10 April 2016, Network for Comfort and Energy Use in Buildings, Cumberland Lodge, Windsor, UK, pp. 445-465.

Daniel, L., Williamson, T., Soebarto, V., & Chen, D., 2015. Learning from thermal mavericks in Australia: comfort studies in Melbourne and Darwin, *Architectural Science Review, 58*(1), pp. 57-66.

Deuble, M P., & de Dear, R J., 2014. Is it hot in here or is it just me? Validating the post-occupancy evaluation. *Intelligent Buildings International, 6*(2), pp. 112-134.

Honjo, M., Rijal, H B., Kobayashi, R., & Nakaya, T., 2012. Investigation of comfort temperature and the adaptive model in Japanese houses. *Proceedings of 7th Windsor Conference: The changing context of comfort in an unpredictable world* 12-15 April 2012. Network for Comfort and Energy Use in Buildings, Cumberland Lodge, Windsor, UK.

Howden-Chapman, P., Roebbel, N., & Chisholm, E., 2017. Setting housing standards to improve global health. *International Journal of Environmental Research and Public Health, 14*(12).

Howden-Chapman, P., Matheson, A., Crane, J., Viggers, H., Cunningham, M., Blakely, T., Cunningham, C., Woodward, A., Saville-Smith, K., O'Dea, D., & Kennedy, M., 2007. Effect of insulating existing houses on health inequality: cluster randomised study in the community. Bmj*,* 334(7591), pp.460.

Kim, J., de Dear, R., Parkinson, T., Cândido, C., Cooper, P., Ma, Z., & Saman, W., 2016. Field Study of Air Conditioning and Thermal Comfort in Residential Buildings. *Proceedings of 9th Windsor Conference: Making Comfort Relevant, Cumberland Lodge*, Windsor, UK, 7-10 April 2016. Network for Comfort and Energy Use in Buildings, Cumberland Lodge, Windsor, UK.

Marmot, M., & Bell, R., 2012. Fair society, healthy lives. Public health*,* 126, pp. S4-S10.

NatHERS, 2012. Nationwide House Energy Rating Scheme (NatHERS) – software accreditation protocol. NatHERS National Administrator. Accessed 8 January 2018, retrieved from: http://www.nathers.gov.au/

Pearlin, L I., & Schooler, C., 1978. The structure of coping. *Journal of Health and Social Behavior,* pp. 2-21.

Thomson, H., Thomas, S., Sellstrom, E., & Petticrew, M., 2009. The health impacts of housing improvement: a systematic review of intervention studies from 1887 to 2007. American *J*ournal of *P*ublic *H*ealth*,* 99(S3), pp. S681-S692.

Wang, Q., Li, C., Guo, Y., Barnett, A G., Tong, S., Phung, D., Chu, C., Dear, K., Wang, X., & Huang, C., 2017. Environmental ambient temperature and blood pressure in adults: A systematic review and meta-analysis. *Science of the Total Environment, 575*, pp. 276-286.

Williamson, T.; & Daniel, L. 2018. Changing thermal comfort expectations: studies in Darwin, Australia. *10th Windsor Conference: Rethinking Thermal Comfort*, full paper accepted 18 February.

Williamson, T J., Coldicutt, S., & Penny R E C., 1989, *Thermal comfort and preferences in housing: South and central Australia.* Adelaide, SA: Department of Architecture, The University of Adelaide.

Yan, H., Mao, Y., & Yang, L., 2017. Thermal adaptive models in the residential buildings in different climate zones of Eastern China, *Energy and Buildings, 141*, pp. 28-38.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Energy and thermal performance of apartment buildings in Albania: the case of a post-communist country

Jonida Murataj[1], Rajat Gupta[2], Fergus Nicol[2]

[1] School of Architecture, Oxford Brookes University, Oxford, UK, jonida.murataj-2015@brookes.ac.uk

[2] Low Carbon Building Group, Oxford Institute for Sustainable Development, Oxford Brookes University, Oxford, UK, rgupta@brookes.ac.uk, jfnicol@brookes.ac.uk

Abstract: This paper undertakes a comparative evaluation of the energy and thermal performance of apartment buildings in Albania built both Pre-90 and Post-91 (a year that marks the change of the political system from communism to democracy in Albania). Building surveys, occupant surveys and continuous monitoring of outdoor and indoor environmental conditions during the summer and winter to allow for seasonal variations, were conducted in 29 case study flats randomly selected to represent both periods. Electricity bills were also provided for a full year. It was found that electricity consumption has been 22% lower in flats built Pre-90 and that the average temperature in living rooms were found to be very close to 29°C in summer and 16°C in winter in both Pre-90 and Post-91. Notwithstanding that measured average temperatures were similar in the two building cohorts, higher range and variance on mean indoor temperature has been found in summer in the flats built Pre-90, which has affected the thermal sensation votes of occupants living in them. It was found that over 60% of residents living in apartment buildings built Pre-90 were feeling cold in winter and hot in summer, compared to 30-40% of residents living in apartment buildings built Post-91, who felt cold in winter and hot in summer respectively. Although the findings cannot be treated as statistical generalization, the analysis provides an in-depth contextual insight into environmental, thermal and energy performances of flats in Albania, which would help inform future energy retrofitting programmes.

Keywords: Energy performance, thermal comfort, occupant's behaviour, apartment buildings, post-communism

1. Introduction

As in many countries in Europe, improving the existing stock in Albania is considered as the highest potential contributor to the energy saving targets of the National Energy Efficiency Plan (Energy Community, 2011), given the fact that building sector is the second largest energy consumers in Albania with over 40% of total carbon emissions (Energy Community, 2015; Global Buildings Performance Network, 2015). Even more, reducing energy reduction in buildings is considered essential to increase the energy security of the country (Energy Charter Secretariat, 2013). Although Albania, as a developing country, has no obligations towards reducing any quantity of greenhouse gas emissions (United Nations Human Rights, 2015), the built area and the energy consumption in the building sector is expected to increase as a result of the continuous development of the country. Moreover, Gupta (2013) remarked that we expect people to spend more time in the buildings in the future in the developing countries, as in developed countries (90% of the time), consequently increasing the energy consumption and health issues.

Furthermore, the economic situation of Albania makes it difficult to consume the necessary amount of energy to provide the adequate thermal comfort in houses. At least 25% of the population cannot afford to pay for energy and 95% of those with access to electricity say it is too expensive to use (Fankhauser and Tepic, 2005). Today, the housing stock is in a poor condition also due to long-term lack of renovation, mainly because of lack of financing for this purpose. Therefore, it is inevitability to improve the energy performance, as well as increase the thermal comfort in the existing homes in Albania.

However, regional, social and cultural variation including differences in climatic conditions, income level, building materials and techniques have probably underestimated (Kohler, 1999) when designing energy retrofitting programmes. In line with this, in a post-communist society, where, on one hand people took control over their lives, property and economy and on the other hand, were left with feelings of weakness and powerless to self-organize because of for a long time previously being controlled by the state, it is important to know whether their expectations of the comfort that their indoor environment must provide has also changed. The last 27 years have marked many changes in Albania, not only in the built environment, but also in the way people live and respond to their environment.

In this context, this paper presents a comparative analysis of energy and thermal performance between the flats built Pre-90 and Post-91. The aim is to create an insight of energy and thermal performance of flats is Albania built during two main political periods and whether there is a correlation between how people feel in terms of thermal comfort and building period. Although flats represent only 6% of the residential buildings in Albania, they accommodate over 35% of the total households in Albania (Novikova et al., 2015). A socio-technical approach consisting of building and occupants' surveys, electricity data' collection, as well as indoor and external temperature measurements, was followed to give an overall picture of environmental, energy and thermal performance of flats across both periods. Statistical analyses have been undertaken to find correlations between them and other factors, such as, demographic, building or behavioural factors.

1.1. Apartment buildings built Pre-90 and Post-91

Most of buildings in Albania, and especially apartment buildings, have been the product of a quick and cheap construction strategy because of the housing shortage during the communist regime (Pre-90) and after, from the rapid urbanization that happened with the beginning of the democracy, which paid no intention to the quality of life of their occupants. Homes built during communist regime (53% of all apartment buildings' stock in Albania) were minimalist, demonstrating the power of the system over people's life and space. The approved standards were 4-6 m^2 per person (United Nations, 2002), causing discomfort of life related to living conditions in them. On the other hand, the size of households were large due to the fact that more than one generation shared the same dwelling (Aliaj, 1999), mainly because for cultural reasons and strong traditional values of marriage and family, as well as economic reasons. Apartment buildings constructed during this period were mainly prototype designs of low-rise blocks of flats, typically with loadbearing brick constructions or pre-fabricated concrete elements.

With the change of the political system to democracy, there was a massive and uncontrolled flow of population from rural to urban areas. Therefore, the biggest intent was to build bigger houses at a low cost, with no concern to neither the design nor energy efficiency nor thermal comfort. Apartment buildings were characterised by high-rise (above 8 floors) concrete frames structures with hollow bricks in-fill and no wall insulation.

Although the Building Code was revised in 1989, the Energy Building Code come to life in 2003, but it was never implemented. Therefore, most of the residential buildings in Albania are uninsulated and built with no concern to energy efficiency. Table 1 gives an overview of building and socio-economic characteristics of both periods considered in this paper.

Table 1: Building and socio-economic characteristics of two main construction periods in Albania

Period	Building characteristics	Socio- economic characteristics
Pre-90	• Low-rise blocks of flats (six floors max) • Typically, loadbearing brick construction or pre-fabricated elements • Prototype designs • Limited space standards • High technical standards due to the strict control • Average household size in the sample is 3.2 members • Average number of bedrooms is 1.6 • Average density is 0.054 people/m^2	• Immigration was totally controlled by the communist government • No housing markets • Big families in small flats • Low-cost buildings • Buildings of this period supported the 'collective' aspect of communism ideology: 'Let's build quickly, good and cheap' slogan
		
Post-91	• Many ground-floor flats were converted to non-residential use • Most common construction is concrete frames with hollow brick in-fill • Limited building controls • Average household size in the sample is 3.4 members • Average number of bedrooms is 1.8 • Average density is 0.049 people/m^2	• Rapid and massive free movement from rural to urban areas • Overpopulation of cities • Most of public stock was privatized • Most new housing has been produced by the private sector • Individualist society
		

2. Methodology

The analysis presented in this paper relate to 29 owner-occupied case study flats out of 49 dwellings selected to represent Albanian housing stock for an on-going research by the authors that aims to investigate the most effective retrofitting strategies for energy savings and improving thermal comfort in residential buildings in Albania. From the group of 29 flats, 13 have been built Pre-90 and 16 Post-91. The year 1990 is taken as the reference year where a massive social, economic and cultural change has happened in Albania affecting also the construction industry, as the result of the political change from the communist regime to democracy.

A socio-technical approach was used to collect quantitative and qualitative data from 29 flats in Tirana, Albania, in summer and winter, in order to have an overall picture of energy and thermal performance of the flats in the most energy consuming seasons of the year. Data collection consisting of:

Building surveys to gather information regarding the building properties and energy use. Quantitative data were collected regarding building materials and construction, orientation, floor area, appliances and lighting, which creates a detailed picture of energy use and behaviours within the flat. The survey was undertaken only once (in June-July) because the information gathered would be the same in both seasons for the same flats. Electricity bills were also obtained for 22 out of 29 flats.

Occupants' survey through questionnaire-guided interviews to get insights of how and when the house has been used, as well as occupants' behaviours in their home. The study adopted the method of questionnaire-guided interviews, as the most appropriate technique for gathering of all essential information in full range and depth, as well as getting insights of occupants' behaviours. The survey included also a transverse questionnaire, with questions to assess their comfort sensation and preference in summer and winter. Only one occupant per dwelling participated in the survey, to provide consistency across the research, and a total of 29 responses for each season was gathered.

Continuous monitoring of the outdoor and indoor temperature in the living room and main bedroom of the flats in summer and winter, to assess the thermal comfort in the house. iButtons, with accuracy of (± 0.5)°C and a measurement range of (-10)°C to (+65)°C, were used to record the indoor temperature of the main living room and bedrooms of the flats in summer and winter for 6 weeks per season at half-hourly intervals to allow for seasonal variations. Data loggers were placed by the researcher in secure places in the living rooms and bedrooms away from external walls, direct solar radiation and devices that generate heat or air conditioning, to minimise any local effects on the measurements. Outside air temperature was also measured at 30-minute interval for 6 weeks in summer and 6 weeks in winter. The decision on the instrument was made on the minimum interference and upsetting of occupants' activities and life, as well as cost.

An overview of data collected for each flat is given in Table 2:

Only the living room measurements are considered for the scope of this study and all the analysis presented in this paper has been undertaken using SPSS Statistics, Version 24.

Table 2: Data collected for each flat

	Building survey	Occupant's survey	Transverse thermal comfort survey		Continuous measurement of living room temperature		Continuous measurement of bedroom temperature		Monthly electricity data
			Summer	Winter	Summer	Winter	Summer	Winter	
F1	√	√	√	√	√	√	√	√	√
F2	√	√	√	√	√	√	√		
F3	√	√	√	√	√	√	√	√	√
F4	√	√	√	√	√	√	√	√	√
F5	√	√	√	√	√	√	√	√	√
F6	√	√	√	√	√	√	√	√	√
F7	√	√	√	√	√	√	√		
F8	√	√	√	√	√	√	√	√	√
F9	√	√	√	√	√	√	√	√	√
F10	√	√	√	√	√	√	√	√	√
F11	√	√	√	√	√	√	√	√	√
F12	√	√	√	√	√	√	√	√	√
F13	√	√	√	√	√	√	√	√	
F14	√	√	√	√	√	√	√	√	√
F15	√	√	√	√	√	√	√		
F16	√	√	√	√	√	√	√	√	
F17	√	√	√	√	√	√	√	√	√
F18	√	√	√	√	√	√	√	√	√
F19	√	√	√	√	√	√	√	√	√
F20	√	√	√	√	√	√	√	√	√
F21	√	√	√	√	√	√	√	√	√
F22	√	√	√	√	√	√	√	√	√
F23	√	√	√	√	√	√	√	√	√
F24	√	√	√	√	√	√	√	√	√
F25	√	√	√	√	√	√	√	√	√
F26	√	√	√	√	√	√	√	√	√
F27	√	√	√	√	√	√	√	√	
F28	√	√	√	√	√	√	√	√	√
F29	√	√	√	√	√	√	√	√	

Flats built pre-1990 (light shading)
Flats built post-1991 (dark shading)

2.1. Survey sample

From 22171 apartment buildings in Albania, over 30% of them are in Tirana (Instat, 2012). Flats were randomly selected form various parts of Tirana, the capital of Albania. Most of them were mixed-used with shops on ground floor and residential on the others. From the sample, 13 flats are built Pre-90 and 16 flats are built Post-91.

Table 3 presents the frequency of different characteristics in the sample. Pre-fabricated concrete panels and solid brick walls were very common constructions during the communist regime of Pre-90, while insulation has only started to be applied in the last ten years or so. Date of construction ranged from 1950 to 2013. Most of the flats have 1-2 bedroom. The household size in the sample is 1-5 members and are of different ages (children to elderly members).

Table 3: Frequency of different characteristics in the sample

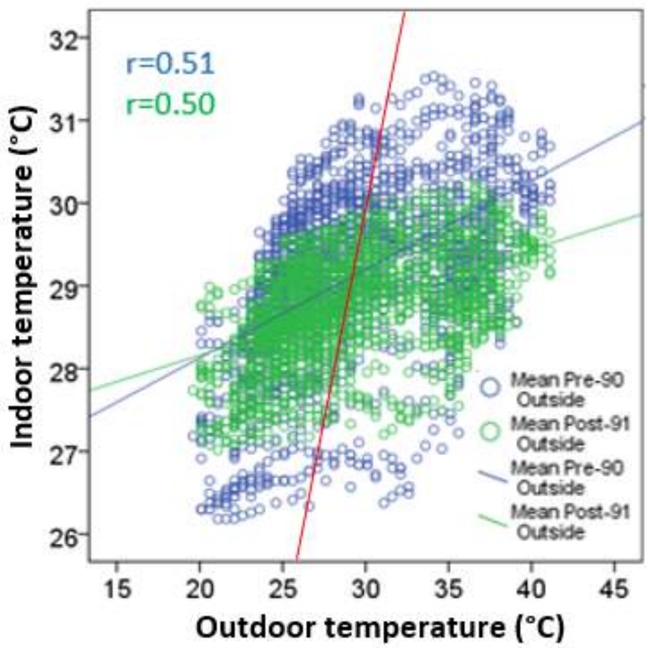
Categories		Count n	Percentage %
Period	Pre-90	13	44.8%
	Post-91	16	55.2%
Main construction material	Stone	0	0.0%
	Full brick	5	17.2%
	Hollow brick	14	48.3%
	Pre-fabricated	3	10.3%
	Hollow brick and insulation	2	6.9%
	Silicate brick	5	17.2%
How many bedrooms?	1 bedroom	10	34.5%
	2 bedrooms	17	58.6%
	3 bedrooms	2	6.9%
What is the highest education level in your household?	Elementary	0	0.0%
	High school	6	20.7%
	University	23	79.3%
Household size	1	2	6.9%
	2	6	20.7%
	3	7	24.1%
	4	9	31.0%
	5	5	17.2%
How many persons younger than 18 live in the household?	0	13	44.8%
	1	9	31.0%
	2	7	24.1%
How many persons older than 65 live in the household?	0	19	65.5%
	1	6	20.7%
	2	4	13.8%
Type of heating	No heating	0	0.0%
	Heat pumps	19	65.5%
	Electric heater	6	20.7%
	Gas heater	0	0.0%
	Wood stove	0	0.0%
	Heat pumps and electric heater	2	6.9%
	Heat pumps and gas heater	1	3.4%
	Individual central heating	1	3.4%
Type of cooling	No cooling	1	3.4%
	Air conditioning	19	65.5%
	Electric cooler	4	13.8%
	Air conditioning and electric cooler	5	17.2%

Electricity was the most commonly type of energy used for space heating mainly due to lack of infrastructure or security for using other types such as gas and wood, and air-conditioning devices are the most common heating and cooling in the flats in the sample. Almost in all dwellings, electricity consumption increases during the winter months (November-March) with its peak in January and in summer (June – August) in July, associated with heating and cooling respectively. The normalised electricity use by area has reached values from 50 to 120kWh/m^2/year in flats built both Pre-90 and Post-91, however the yearly average electricity consumption in flats built Post-91 has been found to be 22% higher than in those built Pre-90.

3. Temperature distribution and thermal comfort during the summer

The indoor temperature of 29 living rooms and 26 main bedrooms were monitored from 30 June to 12 August 2016 at half-hourly intervals, to cover the hottest season of the year in the Albanian climate. The outdoor temperature ranged between 19.6°C to 41.1°C, while the indoor temperature ranged from 23°C to 36.5°C (mean 29.1°C) and 24.5°C to 35.5°C (mean 28.7°C) in living rooms of flats built before and after 1990 respectively.

Figure 1 gives temperature distribution of the whole set of the indoor (living rooms) and outdoor temperature recordings during the summer for both flats built Pre-90 and Post-91, followed by a descriptive analysis of the mean indoor temperature. Each dot represents the average of the recorded temperature of all flats built Pre-90 (blue) and Post-91 (green) every 30 minutes, against the recorded outdoor temperature. It is found a wider range (5.4°C) and larger variance (1.1°C) in the indoor temperatures in flats built Pre-90 compared with flats built Post-91 with range and variance of 3.2°C and 0.4°C respectively.



Descriptive analysis	Average of flats Pre-90	Average of flats Post-91
N	2047	2047
Minimum (°C)	26.2	27.0
Maximum (°C)	31.5	30.2
Mean (°C)	29.1	28.7
Std. Deviation	1.0	0.6
Range	5.4	3.2
Variance	1.1	0.4

Figure 1: Average of recorded indoor temperature of flats built both Pre-90 (blue) and Post-91 (green) plotted against recorded external temperature. The red line shows where the indoor and outdoor temperatures are equal. The table presents the descriptive analysis of the recorded indoor temperatures averaged for flats built in both cohorts

Indeed, there is a higher proportion of indoor temperatures experienced towards the hot end of the spectrum in the flats built Pre-90, as shown in the population pyramid given in Figure 2. The average of the recorded indoor temperature has a wider variance in flats built Pre-90, but it has a higher concentration around 29°C in flats built Post-91.

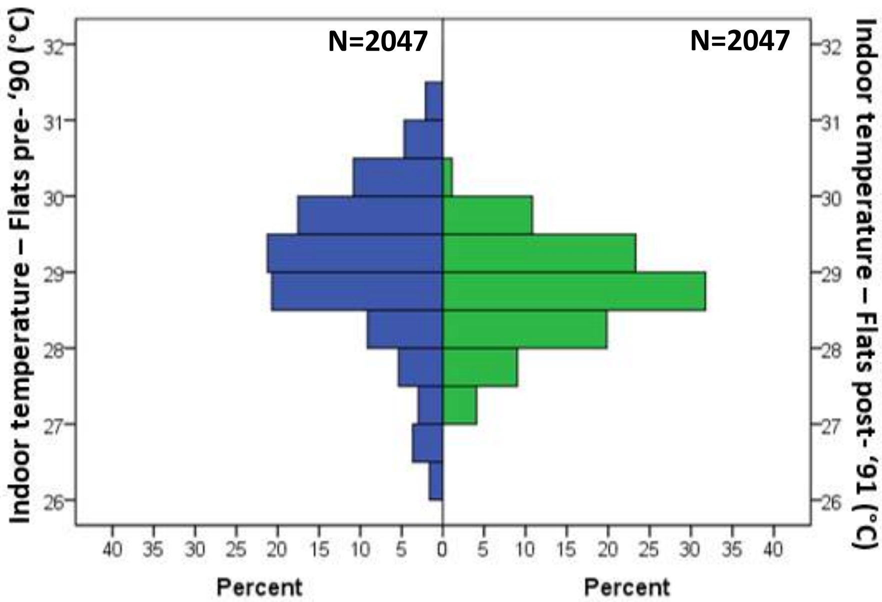


Figure 2: Comparison of indoor averaged indoor temperature distribution in summer between flats built Pre-90 and Post-91

Looking at the running daily mean temperature during the monitoring period (See Figure 3) there are found recorded indoor temperatures above 25°C almost all the time in all the flats, being well above the recommended figures from the guidelines (23°C -25°C) (CIBSE, 2006). Notwithstanding that most of them have the ease with which indoor temperatures can be lowered by adjusting the air conditioning system, indoor temperatures up to 31°C have been found very common in summer. Furthermore, the daily mean temperatures have been up to 1°C higher in flats built pre-1990.

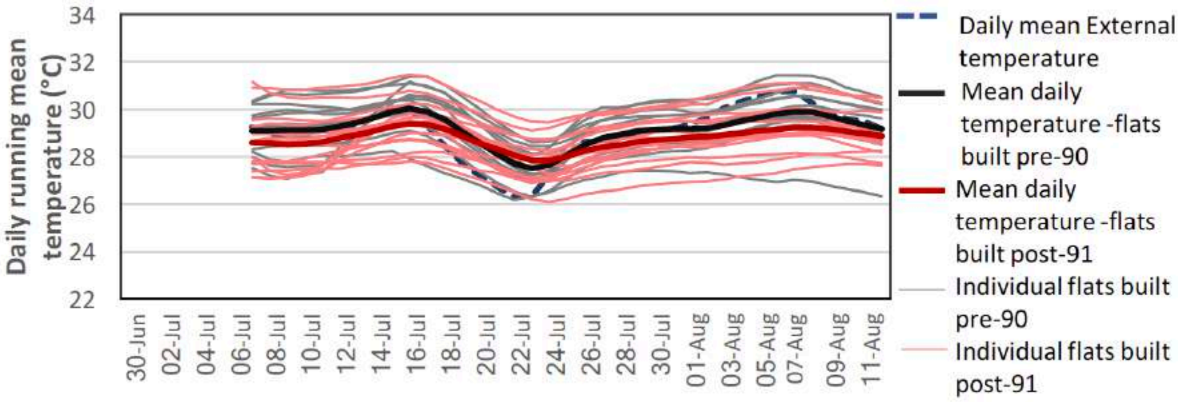
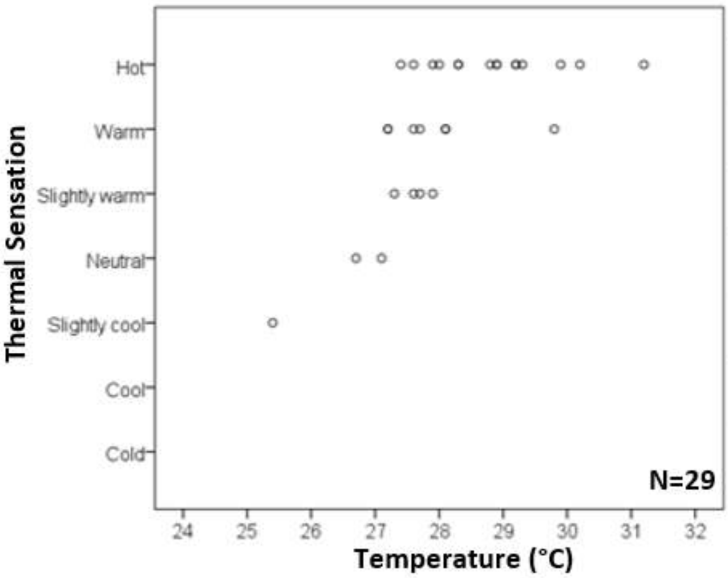


Figure 3: Daily running mean indoor temperatures in summer for each flat and averaged for flats built Pre-90 and Post-91

3.1. Thermal comfort in summer

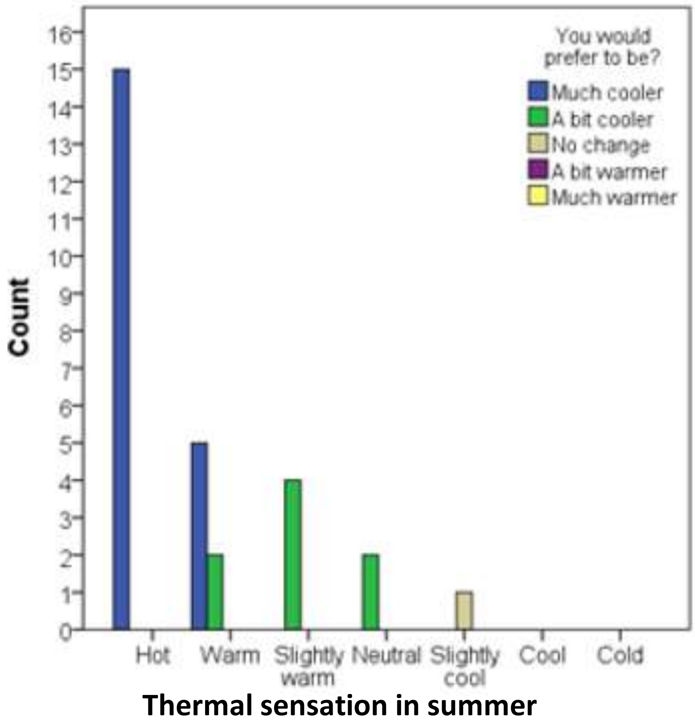
Subjective evaluation of the thermal environment was provided using a 7-point ASHRAE scale for the thermal sensation evaluation and a 5-point scale for thermal preference (ASHRAE, 1992). From the thermal sensation vote distribution given in Figure 4, followed by a descriptive analysis, it is shown that about 90% of the participants reported feeling warmer than neutral during the summer, from which over 50% of them were feeling hot, for a mean temperature of 28.9°C (SD=1.0). Only two occupants were feeling neutral for mean temperature of 26.9°C (SD=0.3) and one slightly cool for mean temperature of 25.4°C.



	(°C)			
n	Mean	s.d.	Min	Max
15	28.9	1.0	27.4	31.2
7	28.0	0.9	27.2	29.8
4	27.6	0.3	27.3	27.9
2	26.9	0.3	26.7	27.1
1	25.4	.	25.4	25.4
0	.	.	.	.
0	.	.	.	.

Figure 4: Total thermal sensation votes in summer and descriptive statistics for each scale

In Figure 5 are shown the thermal preferences votes corresponding with each thermal sensation votes reported during the survey in summer. All the participants that were feeling hot (T=28.9°C) and most of them that were feeling warm (T=28.0°C), wanted to feel much cooler. All the others (T=26.9-28.0°C) wanted to feel a bit cooler, except the person that was feeling slightly cool who wanted no change (T=25.4°C)



N=29

	Much cooler	A bit cooler	No change	Total
Hot	15	0	0	15
Warm	5	2	0	7
Slightly warm	0	4	0	4
Neutral	0	2	0	2
Slightly cool	0	0	1	1
Cool	0	0	0	0
Cold	0	0	0	0
Total	20	8	1	29

Figure 5: Thermal sensation votes reported in summer and crosstabulation with thermal preference votes

Comparing thermal sensation votes of participants living in flats built Pre-90 and Post-91 (Figure 6), it was found that the proportion of people feeling hot was higher in the flats built Pre-90 (70%) than those living in flats built Post-91 (44%). However, the mean temperature was also higher in those flats. Only two persons reported feeling neutral in flats built Post-91 for a mean temperature of 26.9°C.

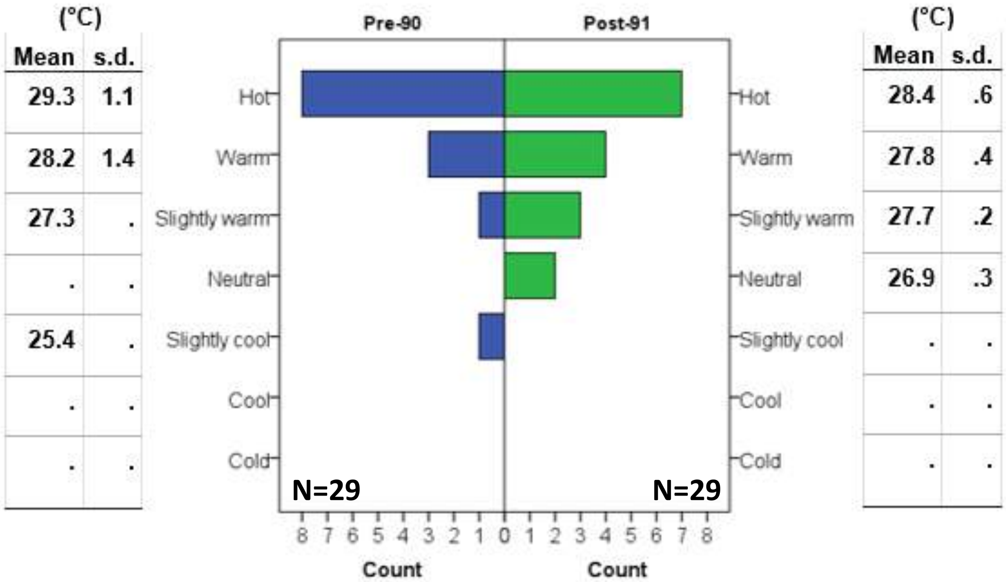


Figure 6: Comparison of thermal sensation votes in summer for flats built Pre-90 and Post-91, together with descriptive statistics of indoor temperature for each ASHRAE thermal sensation scale

A descriptive analysis is given in Table 4, comparing indoor temperature and thermal sensation votes in flats built both Pre-90 and Post-91, for several variables. Interestingly, mean indoor temperature and thermal sensation votes are not affected by the size of the household in both periods.

The presence of children and elder members in the household is higher in the flats built Post-91 and the mean indoor temperature was generally lower in those flats compare to the indoor temperature in flats built Pre-90. However, the thermal sensation in households with children and elder members were higher in flats built Post-91 than those built Pre-90. Over 80% of the flats were air conditioned, however mean indoor temperatures have been over 28°C. There were only three flats where air conditioning was on all day, while most of them were cooled for a few hours mainly in afternoon and evening. Windows were left open for the rest of the time. However, six of the participants reported to open windows and doors all day, even when the cooling was on.

Higher thermal sensation votes and higher mean indoor temperatures (0.5-1°C higher) have been found in air-conditioned flats built Pre-90 compared with flats built Post-91. Interestingly, higher mean indoor temperatures and thermal sensation votes have been found in insulated flats built Post-91 compared to uninsulated ones.

Table 4: The mean and standard deviation of the indoor temperature, and thermal sensation votes for flats built Pre-90 and Post-91, for different variables in summer

	Pre-90						Post-91					
	Temperature (°C)			ASHRAE*			Temperature (°C)			ASHRAE*		
	n	Mean	s.d.	n	Mean	s.d.	n	Mean	s.d.	n	Mean	s.d.
Household size												
1	1	29.8	.	1	3.00	.	1	30.3	.	1	3.00	.
2	3	28.7	.5	3	2.33	.58	3	27.9	.4	3	2.33	.58
3	3	29.1	.9	3	3.00	.00	4	28.8	.4	4	1.50	.58
4	5	29.2	1.2	5	2.00	1.73	4	28.5	.3	4	1.75	1.50
5	1	29.0	.	1	1.00	.	4	29.1	1.4	4	2.25	1.50
How many persons younger than 18 live in the household?												
0	6	29.1	.7	6	2.67	.52	7	28.6	.9	7	1.86	1.07
1	3	28.4	1.2	3	1.67	2.31	6	29.0	1.1	6	2.00	1.26
2	4	29.6	.6	4	2.25	.96	3	28.5	.4	3	2.33	1.15
How many persons older than 65 live in the household?												
0	6	29.5	.7	6	2.67	.52	13	28.8	.9	13	1.85	1.14
1	5	28.9	1.0	5	1.80	1.79	1	27.3	.	1	3.00	.
2	2	28.4	.2	2	2.50	.71	2	29.0	.9	2	2.50	.71
Type of cooling												
No cooling	1	28.6	.	1	2.00	.	0	.	.	0	.	.
Air conditioning	7	29.2	1.0	7	2.14	1.46	12	28.7	.7	12	2.00	1.13
Electric cooler	2	29.2	1.3	2	3.00	.00	2	29.9	.9	2	2.00	1.41
Air conditioning and electric cooler	3	29.0	.7	3	2.33	1.15	2	28.0	1.0	2	2.00	1.41
Are the walls being insulated?												
No	13	29.1	.8	13	2.31	1.18	11	28.7	.8	11	1.82	1.17
Yes	0	.	.	0	.	.	5	28.9	1.1	5	2.40	.89
Have you got double glazing?												
No	11	29.2	.7	11	2.55	.69	7	28.8	1.0	7	2.14	1.21
Yes	2	28.5	1.8	2	1.00	2.83	9	28.7	.8	9	1.89	1.05
When do you switch the cooling on during the day?												
No cooling	0	.	.	0	.	.	2	29.9	.9	2	2.00	1.41
Afternoon	6	29.2	.8	6	2.67	.52	3	28.7	.9	3	2.33	.58
Evening	1	29.3	.	1	2.00	.	1	28.6	.	1	.00	.
Afternoon + evening	4	29.1	.6	4	2.50	1.00	9	28.7	.7	9	2.00	1.12
All day	2	28.6	2.0	2	1.00	2.83	1	27.3	.	1	3.00	.
Do you cool the house during the night?												
No	10	29.2	.7	10	2.70	.48	11	28.8	.7	11	2.00	1.00
Yes	3	28.7	1.4	3	1.00	2.00	5	28.5	1.2	5	2.00	1.41
When do you open the windows in summer?												
Afternoon	1	28.9	.	1	3.00	.	1	28.7	.	1	1.00	.
Evening	0	.	.	0	.	.	1	30.3	.	1	3.00	.
During the night	1	27.2	.	1	-1.00	.	0	.	.	0	.	.
Morning + evening	4	29.5	.2	4	2.75	.50	7	28.6	.5	7	1.43	1.27
All day	3	29.1	.9	3	2.33	1.15	3	29.0	.6	3	2.67	.58
All day and night	3	29.5	.9	3	2.33	.58	1	30.5	.	1	3.00	.
Evening and night	1	28.4	.	1	3.00	.	3	27.8	.6	3	2.33	.58

*ASHRAE seven-point scale: Hot=3; Warm=2; Slightly warm=1; Neutral=0; Slightly cool=-1; Cool=-2; Cold=-3

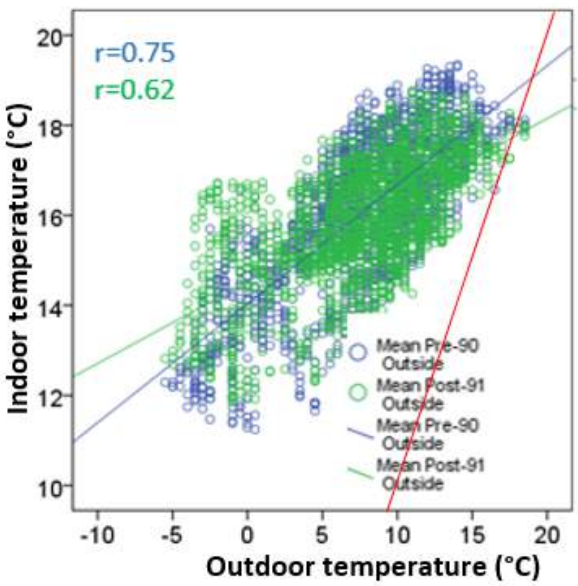
On the other hand, the presence of double glazing might have affected the indoor temperatures and thermal sensation votes, as they were higher for flats with single glazing compared to those with double glazing. Expectable, flats that had cooling on all day, had lower indoor temperatures, compared to those that had cooling on only for some hours a day. Notwithstanding that indoor temperature has been lower in the flat built Post-91 that had cooling on all day, the occupant participating in the survey reported to feel hot. From 29 flats (13 built Pre-90 and 16 built Post-91), most of them have been not cooled during the night in summer and the thermal sensation votes have been higher in flats built Pre-90 compared to those built Post-91. Opening the windows all day, have caused the indoor temperature to be higher, associated with higher thermal sensation votes, in both cohorts. In the other hand, opening the windows only during the night has resulted in lower indoor temperatures and thermal sensation votes.

4. Temperature distribution and thermal comfort during the winter

The indoor temperature of 29 living rooms have been monitored from 5 January to 16 February 2017 at half-hourly intervals, to cover the cold season. The outdoor temperature ranged between -5.5°C to 18.5°C, while the indoor temperature ranged from 4.5°C to 28°C (mean 16.1°C) and 2.5°C to 27.5°C (mean 15.9°C) in living rooms of flats built Pre-90 and Post-91 respectively.

The same analysis approach as per summer is taken also for the data collected during the winter survey. Figure 7 gives temperature distribution of the whole set of the indoor and outdoor temperature recordings during the winter for both flats built Pre-90 and Post-91, followed by a descriptive analysis of the mean indoor temperature.

Notwithstanding that there has been found a very close mean indoor temperature to 16°C for flats built in both cohorts, there is a wider range and variance of the mean indoor temperatures of flats built Pre-90 (8.1°C and 2.7°C respectively) compared to the range and variance of flats built Post-91 (7°C and 1.8°C respectively).



Descriptive analysis	Average of flats Pre-90	Average of flats Post-91
N	2048	2048
Minimum (°C)	11.3	11.9
Maximum (°C)	19.4	18.8
Mean (°C)	16.1	15.9
Std. Deviation	1.6	1.4
Range	8.1	7.0
Variance	2.7	1.8

Figure 7: Average of recorded indoor temperature of flats built both Pre-90 (blue) and Post-91 (green) plotted against recorded external temperature. The red line shows where the indoor and outdoor temperatures are equal. The table presents the descriptive analysis of the recorded indoor temperatures averaged for flats built in both cohorts during the winter

The correlation r between the indoor and the outdoor temperature is noticeably higher in winter than in the summer. This suggests that the indoor temperature is more influenced by the outdoor temperature in winter than in summer. The similarity in temperature distribution is also illustrated in the population pyramid shown in Figure 8. The mean indoor temperatures are between 14°C and 18°C for most of the time in flats of cohorts.

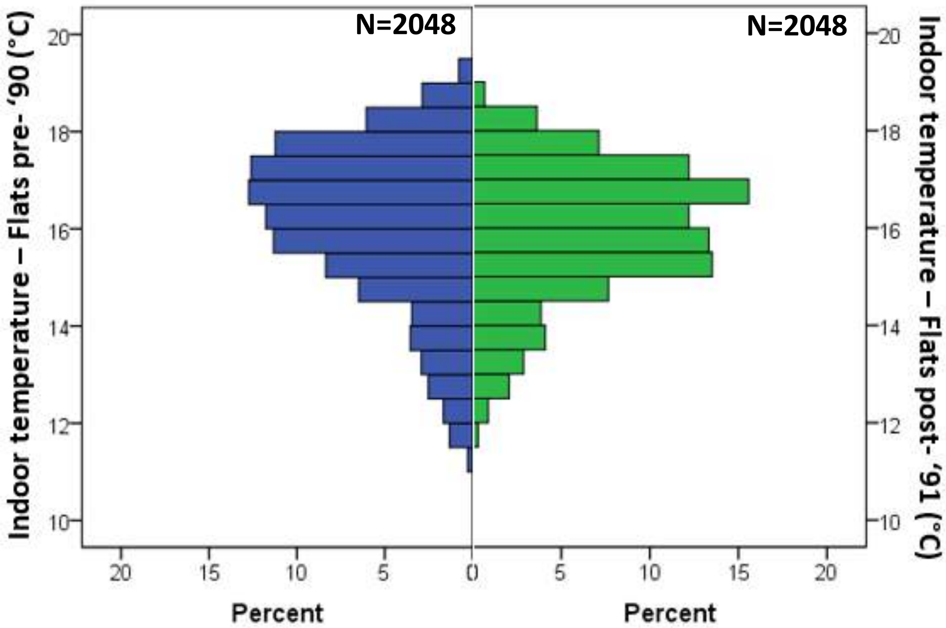


Figure 8: Comparison of indoor temperature distribution in winter between flats built Pre-90 and Post-91

Figure 9 give a line graph of recorded temperature of each flat distinguished by line colours representing flats built Pre-90 and Post-91. Generally, indoor temperature recorded in flats built Pre-90 reach lower values than the flats built Post-91, except two flats built Post-91 that have recorded very low indoor temperatures throughout the monitoring period. The flats were occupied by working couples that typically returned home in evenings.

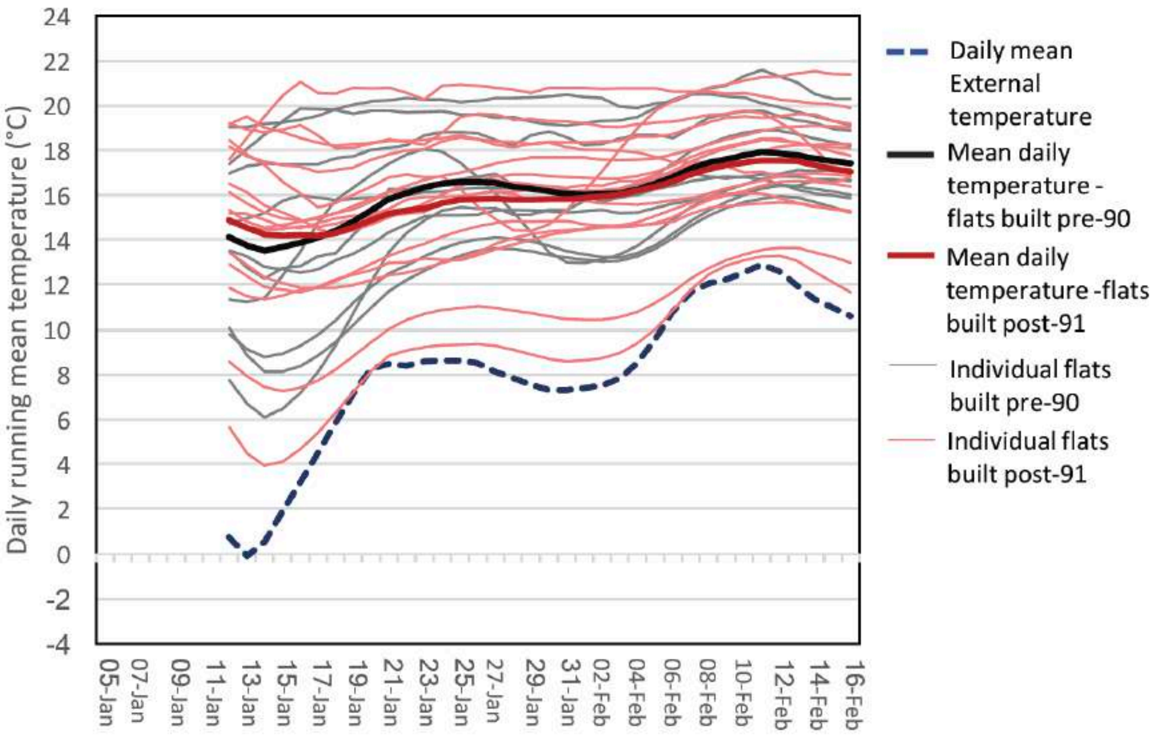
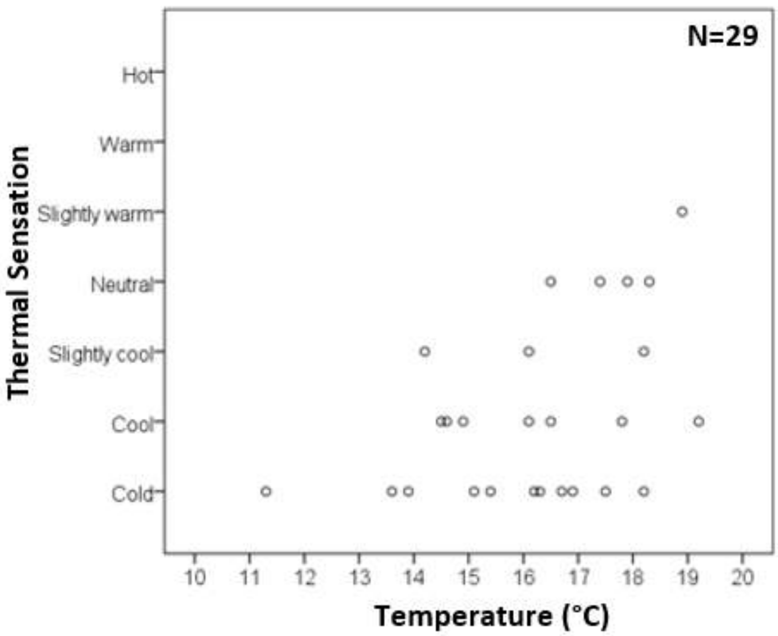


Figure 9: Daily running mean indoor temperatures in winter for each flat and averaged for flats built Pre-90 and Post-91

4.1. Thermal comfort in winter

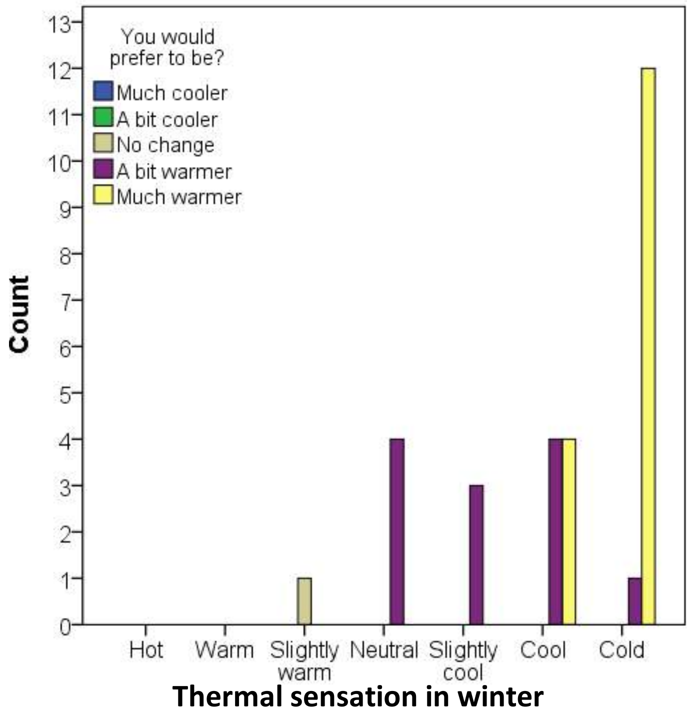
Subjective evaluation of the thermal environment was provided using the 7-point ASHRAE scale for the thermal sensation evaluation and a 5-point scale for thermal preference. From the thermal sensation vote distribution given in Figure 10, followed by a descriptive analysis, it is shown that over 80% of the households reported to feel colder than neutral during the winter, from which about 45% of them were feeling cold, for a mean temperature of 15.6°C (SD=2.0). Only four occupants were feeling neutral for mean temperature of 17.5°C (SD=0.8) and one slightly warm for mean temperature of 18.9°C.



n	Mean (°C)	s.d.	Min	Max
0	.	.	.	.
0	.	.	.	.
1	18.9	.	18.9	18.9
4	17.5	.8	16.5	18.3
3	16.2	2.0	14.2	18.2
8	16.2	1.8	14.5	19.2
13	15.6	2.0	11.3	18.2

Figure 10: Total thermal sensation votes in winter and descriptive statistics for each scale

Thermal preferences votes corresponding with each thermal sensation votes reported during the survey in winter are shown in Figure 11. Only one of the participants was feeling cold (T=15.6°C) and wanted to feel a bit warmer, while all the others wanted to feel much warmer. On the other hand, the participant that was feeling slightly warm (T=18.9°C), wanted no change. Half of the respondents feeling cool (T=16.2°C) wanted to be much warmer, while all other respondents wanted to feel a bit warmer.



N=29

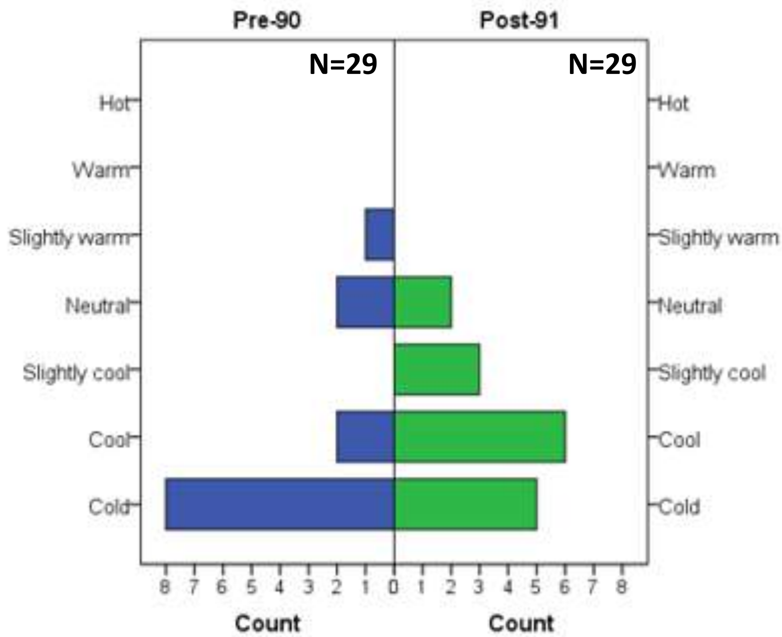
	No change	A bit warmer	Much warmer	Total
Hot	0	0	0	0
Warm	0	0	0	0
Slightly warm	1	0	0	1
Neutral	0	4	0	4
Slightly cool	0	3	0	3
Cool	0	4	4	8
Cold	0	1	12	13
Total	20	8	1	29

Figure 11: Thermal sensation votes reported in winter and crosstabulation with thermal preference votes

Comparing thermal sensation votes of participants living in flats built Pre-90 and Post-91 (Figure 12), it was found that the proportion of people feeling cold was higher in the flats built Pre-90 (62%) than those living in flats built Post-91 (31%), even though, the mean temperature corresponding to the thermal sensation vote (cold) was one degree higher in flats built Pre-90 (T=16°C) than in flats built Post-91 (T=15°C). Only two persons in each cohort reported to feel neutral, and the neutral temperature was slightly higher in flats built Post-91 that those Pre-90.

(°C)

Mean	s.d.
.	.
.	.
18.9	
17.2	1.0
.	.
14.6	1
16.0	2.5



(°C)

Mean	s.d.
.	.
.	.
.	.
17.9	0.6
16.2	2.0
16.9	1.7
15.0	1.3

Figure 12: Comparison of thermal sensation votes in winter for flats built Pre-90 and Post-91, together with descriptive statistics of indoor temperature for each scale

A descriptive analysis is given in Table 5, comparing indoor temperature and thermal sensation votes in both flats built Pre-90 and Post-91, affected by several variables. Most of the households are made of three or more members. The mean indoor temperature is correlated in opposite directions with the household size for flats built Pre-90 and Post-91. It decreases with larger households in flats built Pre-90 and increases in flats built Post-91. However, the thermal sensation votes increase from cold to cool (-3 to -2) for larger households in both flats built Pre-90 and Post-91. For larger households, the mean indoor temperature is lower in flats built Pre-90 and higher in flats built Post-91. Interestingly, the mean indoor temperature is higher (19.2°C) in households made of three members compared to smaller and larger households built Pre-90. Commonly, these families are made of two parents and a child, and tend to create more comfortable thermal conditions than in the other flats. In fact, the presence of children in the household shows to affect the indoor temperatures, but the same cannot be said for the presence of the elder person. Out of 29 households, 16 had a least one child and ten of them had at least one elder member. The mean indoor temperature shows a decrease for their presence. Moreover, there is a lower thermal sensation vote from the households made of children and elder persons.

All flats used convective heating using air conditioning and electric heater devices to heat the space in winter. Even the flat that had individual central heating, was fuelled by electricity. The mean indoor temperature in dwelling that used air conditioning devices has been 1°C lower in flats built Pre-90 (T=15.9°C) compared to those built Post-91 (T=16.9°C) and they had the same thermal sensation vote (-2).

There have been almost the same mean indoor temperature and thermal sensation votes for flats without wall insulation in flats of both cohorts. However, has been a higher mean indoor temperature (T=16.5°C) for flats with wall insulation and higher thermal sensation vote (-1.8). the presence of double glazing has possibly highly affected the mean indoor temperature in flats built Post-91 (T=17°C), compared to mean indoor temperature of 24.8°C in flats with single glazing of the same cohort. In the contrary, a difference of only one degree is found in the mean indoor temperature of flats with (T=16.8°C) and without (T=15.9°C) double glazing in flats built Pre-90. In flats built both Pre-90 and Post-91, the thermal sensation votes are higher for the presence of double glazing.

Higher mean indoor temperatures and thermal sensation votes are associated with flats that are heated in evenings. Two flats built Pre-90 heat the space all day and this is also reflected in higher mean indoor temperatures (18.5) and thermal sensation votes (-1).

Table 5: The mean and standard deviation of the indoor temperature, and thermal sensation votes for flats built Pre-90 and Post-91, for different variables in winter

	Pre-90						Post-91					
	Temperature (°C)			ASHRAE*			Temperature (°C)			ASHRAE*		
	n	Mean	s.d.	n	Mean	s.d.	n	Mean	s.d.	n	Mean	s.d.
Household size												
1	1	16.6	.	1	-3.00	.	1	.	.	1	-2.00	.
2	3	15.3	.4	3	-2.33	.58	3	14.9	1.3	3	-1.67	.58
3	3	19.2	.9	3	-2.00	1.73	4	15.7	4.4	4	-1.50	1.29
4	5	14.6	1.7	5	-2.20	1.79	4	16.3	4.0	4	-2.50	1.00
5	1	13.4	.	1	.00	.	4	16.7	1.8	4	-1.75	1.26
How many persons younger than 18 live in the household?												
0	6	17.3	2.3	6	-2.17	1.17	7	15.9	1.6	7	-1.86	1.07
1	3	17.7	1.1	3	-1.67	2.31	6	15.9	3.6	6	-1.67	1.03
2	4	13.7	.7	4	-2.25	1.50	3	16.4	4.9	3	-2.33	1.15
How many persons older than 65 live in the household?												
0	6	15.9	2.8	6	-2.83	.41	13	15.9	3.3	13	-1.77	1.09
1	5	16.5	2.4	5	-1.00	1.87	1	16.8	.	1	-3.00	.
2	2	15.0	.	2	-2.50	.71	2	15.9	2.2	2	-2.00	.00
Type of heating												
No heating	0	.	.	0	.	.	0	.	.	0	.	.
Air conditioning	8	15.9	2.3	8	-2.00	1.60	11	16.9	2.7	11	-2.00	1.00
Electric heater	4	17.2	2.6	4	-2.75	.50	2	11.8	3.5	2	-1.50	.71
Gas heater	0	.	.	0	.	.	0	.	.	0	.	.
Wood stove	0	.	.	0	.	.	0	.	.	0	.	.
AC + electric heater	1	13.4	.	1	.00	.	1	16.3	.	1	.00	.
AC + gas heater	0	.	.	0	.	.	1	16.8	.	1	-3.00	.
Central heating	0	.	.	0	.	.	1	14.0	.	1	-2.00	.
Are the walls being insulated?												
No	13	16.1	2.4	13	-2.08	1.44	11	15.8	3.2	11	-1.91	1.22
Yes	0	.	.	0	.	.	5	16.5	2.9	5	-1.80	.45
Have you got double glazing?												
No	11	15.9	2.6	11	-2.27	1.19	7	14.8	3.6	7	-2.57	.79
Yes	2	16.8	.2	2	-1.00	2.83	9	17.0	2.2	9	-1.33	.87
When do you switch the heating on during the day?												
Morning	1	16.6	.	1	-3.00	.	0	.	.	0	.	.
Afternoon	1	19.2	.	1	.00	.	2	12.8	4.9	2	-.50	.71
Evening	2	16.7	2.4	2	-2.50	.71	5	15.2	1.1	5	-2.00	.71
Morning and evening	4	13.6	.8	4	-2.25	1.50	5	18.8	.8	5	-1.80	1.30
All day	2	18.5	2.3	2	-1.00	2.83	0	.	.	0	.	.
Afternoon and evening	3	14.8	1.1	3	-2.67	.58	4	14.8	3.0	4	-2.50	.58
Do you heat the house during the night?												
No	12	15.7	2.1	12	-2.00	1.48	12	16.4	2.6	12	-2.00	.95
Yes	1	20.1	.	1	-3.00	.	4	14.7	4.0	4	-1.50	1.29
When and for how long do you open the windows in winter?												
Morning	12	16.2	2.5	12	-2.08	1.51	15	15.8	3.1	15	-1.80	1.01
All day	1	15.0	.	1	-2.00	.	0	.	.	0	.	.
When it is too hot	0	.	.	0	.	.	1	18.3	.	1	-3.00	.

*ASHRAE seven-point scale: Hot=3; Warm=2; Slightly warm=1; Neutral=0; Slightly cool=-1; Cool=-2; Cold=-3

5. Discussion

First of all, the analysis undertaken in this study has demonstrated the 'bad' environmental performance of flats in Albania, regardless the construction cohort. Very high indoor temperatures were recorded during the summer reaching 36.5°C and very low indoor temperature down to 2.5°C in winter. However, it was found that the indoor temperatures in flats built Pre-90 had an elevated temperature range and variation, especially in summer. The flats were constantly overheated, with indoor temperatures over 25°C all the time in summer. A better picture is in winter, where the mean indoor temperatures in most of the flats were above 15°C. The low range and variance of the indoor temperatures during the summer have probably affected the lower proportion of participants feeling hot during the summer in flats built Post-91 (44%) compared to those built Pre-90 (70%). Moreover, the occupants were feeling neutral for indoor temperature close to 27°C. The same thermal performance has been found in winter in flats built Pre-90, where 60% of the participants reported to feel cold. In contrary, only 30% of them were feeling cold in flats built Post-91.

Interestingly, the mean of normalised electricity use by floor area was found non-statistically significance different in flats built in both cohorts, even though the average yearly electricity consumption has been found to be 22% higher in flats built Post-91.

Therefore, what makes the flats built Pre-90 perform worse that those built Post-91 in terms of environmental and thermal performance?

Firstly, the deteriorated conditions of flats built Pre-90, the lack of wall insulation and lack of double glazing have made their contribution in their indoor environmental and thermal performance.

Secondly, seven out of 13 flats (46%) in the sample built Pre-90 were occupied by the same family since they were constructed and had at least one elder member. Usually they wear heavier clothing in summer than younger persons, probably causing thermal discomfort. Furthermore, the clothing norms have changed over the years. Younger people might wear only a sleeveless vest when are indoors, while this could be different for elder people.

Thirdly, the indoor temperature is higher in summer and lower in winter in flats built Pre-90 than in flats built Post-91 because of the shorter time of cooling and heating the space respectively. This is also reflected in considerably lower electricity bills (22%) compared to flats built Post-91.

6. Conclusions

It has been acknowledged that behavioural and social factors affect home energy consumption by as much as ±50% (Gill et al., 2010). Therefore, understanding the context is important not only for more accurate energy reductions by the proposed energy retrofits, but also to indicate the ways people adapt their environment (Nicol and Roaf, 2017). The analysis in this paper was focused on two main periods of Albanian political, economic and social life, that have inevitably affected also the construction industry and typology. Although the number of cases is relatively small, and the findings cannot be treated as statistical generalization, the analysis provides an in-depth contextual insight into environmental, thermal and energy performances of flats in Albania, and discusses the factors affecting them. However, conducting a study with a sample that can be statistically representative of the population would be needed to create a body of evidence on the energy and environmental performance of apartment buildings in Albania, which would help inform future energy retrofitting programmes. Furthermore, a detailed field study of thermal comfort would be essential to determine the range of temperature that people find comfortable in homes in Albania.

Acknowledgements

The authors would like to thank all the homeowners that took part in the survey for their contribution during the study.

References

Aliaj, B. (1999) 'Housing Models in Albania between 1945-1999', *ENHR/MRI Conference*. Balatonfüred, Hungary, pp.

ASHRAE (1992) 'Standard 55 - Thermal Environmental Conditions for Human Occupancy'. Atlanta: ASHRAE Inc.

CIBSE (2006) 'Environmental design: CIBSE Guide A'. Norwich: CIBSE. Available at: http://www.cambeep.eng.cam.ac.uk/References/cibse.

Energy Charter Secretariat (2013) 'In-Depth Review of the Energy Efficiency Policy of ALBANIA '. Brussels: Energy Charter Secretariat. Available at: http://aea-al.org/depth-review-energy-efficiency-policy-albania/.

Energy Community 2011. Synthesis of the assessment of Contracting Parties' Energy Efficiency Action Plans as required by the Energy Community Ministerial Council Decision D/2009/05/MC-EnC of 18 December 2009 on the implementation of certain Directives on Energy Efficiency.

Energy Community (2015) 'Albania: Energy efficiency facts and figures', Available at: https://www.energy-community.org/portal/page/portal/ENC_HOME/MEMBERS/PARTIES/ALBANIA

Fankhauser, S. and Tepic, S. (2005) 'Can poor consumers pay for energy and water? An affordability analysis for transition countries', Available at: http://www.ebrd.com/downloads/research/economics/workingpapers/wp0092.pdf

Gill, Z. M.*, et al.* (2010) 'Low-energy dwellings: the contribution of behaviours to actual performance', *Building Research & Information,* 38(5), pp. 491-508. doi: 10.1080/09613218.2010.505371.

Global Buildings Performance Network (2015) 'Deep Building Renovation: International Policy Guidelines'. Paris, France. Available at: http://www.gbpn.org/sites/default/files/6.DR%20IntPolGuidel_Cover_Report.pdf.

Instat (2012) 'Population and housing census 2011'. Tirana: Insituti i Statistikes. Available at: http://www.instat.gov.al/media/177354/main_results__population_and_housing_census_2011.pdf (Accessed: 10/10/2015).

Kohler, N. (1999) 'The relevance of Green Building Challenge: an observer's perspective', *Building Research & Information,* 27(4-5), pp. 309-320. doi: 10.1080/096132199369426.

Nicol, J. F. and Roaf, S. (2017) 'Rethinking thermal comfort', *Building Research & Information,* 45(7), pp. 711-716. doi: 10.1080/09613218.2017.1301698.

Novikova, A.*, et al.* (2015) 'The typology of the residential building stock in Albania and the modelling of its low-carbon transformation': Regional Environmental Center.

United Nations (2002) 'Country profiles on housing sectors: Albania': United Nations. Available at: http://www.unece.org/fileadmin/DAM/hlm/documents/2002/ece/hbp/ece.hbp.130.e.pdf.

United Nations Human Rights (2015) 'Contribution from the Republic of Albania to the OHCHR analytical study in implementing Resolution 7/23 of the Human Rights Council', Available at: http://www.ohchr.org/Documents/Issues/ClimateChange/Submissions/Albania.pdf

Université Total 2013. Energy efficiency: implications for cities and mobility in tomorrow's world?

AFTER DINNER EVENT

QUIZ NIGHT

Hosts: Atze Boerstra,
Wouter van Marken Lichtenbelt
and Craig Farnham

WORKSHOP 7

Health Physiology and Comfort:
Real Life impacts

Invited Chairs:
Wouter van Marken Lichtenbelt
and Yingxin Zhu

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Creating comfort and cultivating good health: The links between indoor temperature, thermal comfort and health.

Rachel Bills[1]

[1] School of Architecture and Built Environment, University of Adelaide, South Australia

Abstract: There is a growing body of evidence that suggests human thermal requirements change as with age. This study aims to determine the conditions which will provide both a comfortable and healthy environment for the increasing number of older people in Australia. A longitudinal study of thermal comfort and its relationship to health in 18 older households was undertaken in Adelaide, South Australia during 2015 and 2016. The comfort vote survey included measures of thermal comfort as well as a checklist of symptoms experienced in the last 24 hours. These surveys were matched to environmental measurements from the homes. Results show two important relationships between thermal conditions and health: 1. A quadratic relationship exists between reported symptoms and minimum and maximum indoor temperatures in the 24 hours proceeding the reported symptoms. These data indicate that both low and high indoor temperatures may be related to the health of the occupants; 2. A quadratic relationship also exists between the thermal sensation vote and the reporting of symptoms. This research presents evidence that even with Adelaide's relatively mild winters, cold temperatures can have an impact on health, as well as the more extreme summer temperatures. This has implications for healthy housing design for an ageing population.

Keywords: ageing, thermal comfort, health

1. Introduction

Australia, like most countries in the developed world, has an increasing population of people aged 65 or over. People aged over 65 currently represent 15% of the population, and is expected to increase to more than 22% in 2055 (Commonwealth of Australia 2015). This demographic change poses challenges in many areas, including health and housing. It is the preference of most older Australians to 'age in place' and remain independent as long as possible. Given the known relationships between housing and health, it is thus important to determine whether the current housing available to older people is a healthy environment to age in. This study considers the thermal comfort of the occupants as well as their self-reported health in order to examine which conditions may create a healthy, comfortable environment for people as they age in place.

As humans age, physiological changes result in altered thermal perception. The metabolism slows and thermoregulatory changes occur more slowly in older people than in younger adults (Dufour & Candas 2007). Whilst the earliest thermal comfort studies concluded there was no difference between the thermal comfort of older people compared to younger adults (Fanger 1973), more recent evidence shows decreased temperature discrimination amongst older people as well as altered responses to thermal stimuli (Natsume et al. 1992). Differences in thermal comfort amongst older people have been shown to exist, some show a preference for warmer conditions (Schellen et al. 2010) whilst others show cooler conditions are preferred (Bills 2016; Hwang & Chen 2010). These differences may be explained by variables such as context, expectation, acclimation, and the perceived ability to control the thermal conditions (Indraganti 2011).

There are well established links between housing and health, and temperature and health. Morbidity and mortality increase both during periods of extreme heat and prolonged periods of cold temperatures (Nitschke et al. 2007; Wilkinson et al. 2004), whilst various poor housing conditions, such as damp and poorly ventilated houses also contribute to poor health outcomes (Howden-Chapman 2004). Programs which have aimed to improve the quality of housing in regards to temperature control and increased insulation have shown improvements in occupant health (Critchley et al. 2007).

Since there are known impacts of housing conditions and temperature on health, it is thus important to ensure that the houses of older people provide conditions which will foster good health. However since it is also becoming apparent that older people perceive thermal sensations differently to their younger counterparts, it is important to understand what conditions will provide thermal comfort as well. This study aimed to determine the conditions at which older people were comfortable, and the conditions that minimised the presence of symptoms, to determine if an overlap in the conditions exists. The objective is to recommend a range of conditions which could then be applied in future policy decisions such as housing improvement, fuel subsidies, aged care and building regulations.

2. Adelaide in Context

Adelaide, South Australia is the 5th largest population centre in Australia with 1.3 million residents. The city has a larger proportion of people aged over 65 than the country's average, and it is growing at a faster rate than the Australian average (Government of South Australia 2017). According to the city's 30 year plan, this means a greater emphasis needs to be placed on affordable and appropriate housing for ageing in place, which is the preference of most older Australians. New buildings will be needed to accommodate this ageing population, but the existing housing stock cannot be ignored as its redevelopment is unlikely and it should also be able to provide affordable living for older people as well as a healthy environment for ageing in place.

Adelaide has a Köppen climate classification of Csa, with mild cool winters and warm to hot summers (Sturman & Tapper 2006). This climate has historically led to houses which cope better in the summer months than in the cooler months, although more recent buildings are likely to be air conditioned rather than relying entirely on passive methods of temperature control. Most houses are fitted with some sort of cooling and heating appliances, however in older houses these tend to be retrofitted rather than centralised systems. The usage of these systems by older people has been explored in this study as such patterns can help inform design decisions both for new developments and for improving existing houses.

3. Methodology

Research was carried out in two stages: a survey of housing and health amongst Adelaide residents aged 65 and over, and a field study into the thermal comfort and health of some of the survey participants.

3.1. Participants

Participants aged 65 and over were recruited to complete a survey of housing and health, as part of which they could volunteer for the field study. The survey included a range of questions about their house, summer and winter comfort, heating and cooling appliances as well as questions regarding self-reported health and illness. Survey recruitment was conducted with the assistance of local councils, church and social groups. From these survey responses, a total of 18 households were recruited for the field study with 22 participants (11 male, 11 female) across these households. Data were collected between February 2015 and September 2016.

3.2. Field Study

Air temperature, humidity and globe temperature were recorded by unobtrusive data loggers in the bedroom and living areas in the houses of all participants (shown in Figure 1). These recorded conditions every 15 minutes. Participants were asked to regularly complete a comfort vote survey, which included measures of thermal comfort, preference and acceptability including the ASHRAE 7-point thermal sensation scale and the McIntyre 3-point thermal preference scale. Participants were also asked to indicate whether cooling or heating devices were in use, whether windows and doors were open and whether fans were in use. Participants were asked to indicate their current clothing level and recent activity level via diagrams of typical clothing and activities.

Participants were also asked to indicate whether they had experienced any health related symptoms in the previous 24 hours; they were provided with a list of known heat and cold related symptoms as well as a space to indicate other symptoms as they felt necessary. This list was compiled from a previous study which examined health effects of heat waves (Nitschke et al. 2014) with some symptoms added to reflect what is known about cold weather and its associated illnesses (Koskela 2007).

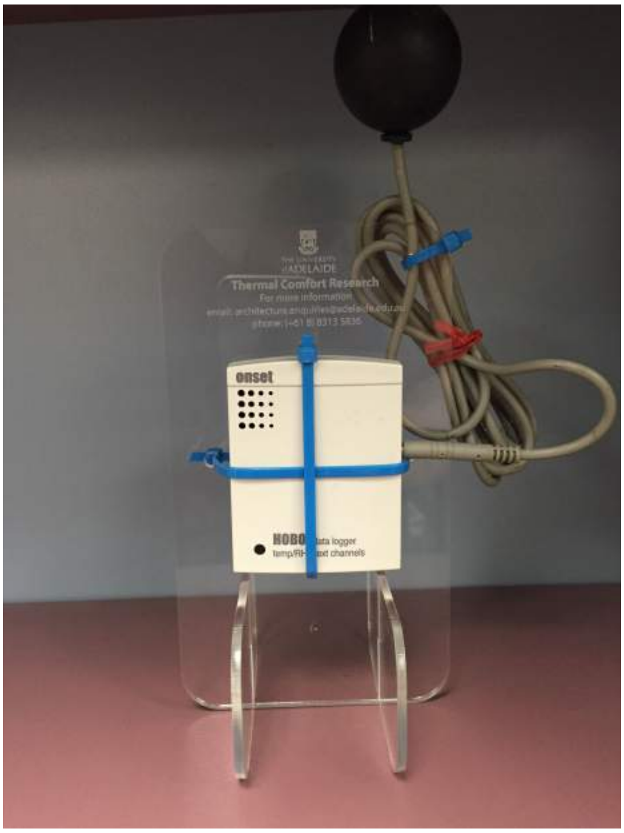


Figure 1 Data logger as placed in participants houses. Photo by author

3.3. Analysis

Survey data were analysed to determine any patterns of heating and cooling use that could impact on the health of the occupants. This included when heating and cooling devices were used and what temperature thermostats were set.

The data from the thermal comfort votes was matched with the temperature and humidity measurements from the data loggers. The previous day's minimum, maximum and average temperatures were also matched to each vote. These votes were then weighted to determine the average neutral temperature of the cohort. Votes were then filtered by whether symptoms were recorded. Those who reported chronic symptoms were excluded from further analysis, as these were not necessarily related to indoor conditions. Thus the results reported represent only the participants who did not report chronic symptoms. This allows clear relationships between conditions and symptoms to be investigated.

The number of votes where symptoms were reported was compared to the total number of votes for each criteria (TSV, maximum temperature, minimum temperature) to determine what percentage of votes presented with symptoms. These results were then graphed and regression analysis was performed.

4. Results

A total of 80 survey responses were collected and a total of 2667 thermal comfort votes were received from field study participants.

4.1. Patterns of heating and cooling use

An analysis of the typical pattern of heating and cooling appliance use was undertaken to determine the preference of the survey participants to use their appliances frequently or to utilise other methods to heat and cool their houses. Very few of the participants in the survey left their heating or cooling running continuously, preferring to use these systems largely in response to their own comfort. Over 40% of participants only turned on heating or cooling when they felt too hot (Figure 2) or too cold (Figure 3). Many participants only used their appliances during the day, and this same trend was noted amongst the field study participants. During the field study heating or cooling use was reported in the bedrooms 20% of the time and 30% of the time in living areas. This indicates a greater reliance on adaptive behaviours amongst these participants than on heating and cooling appliances.

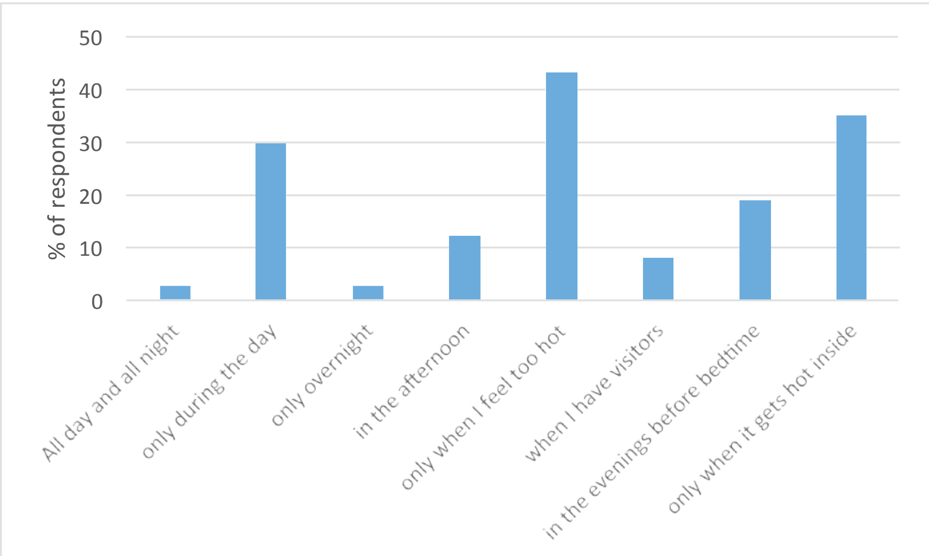


Figure 2 Air conditioning (cooling) use

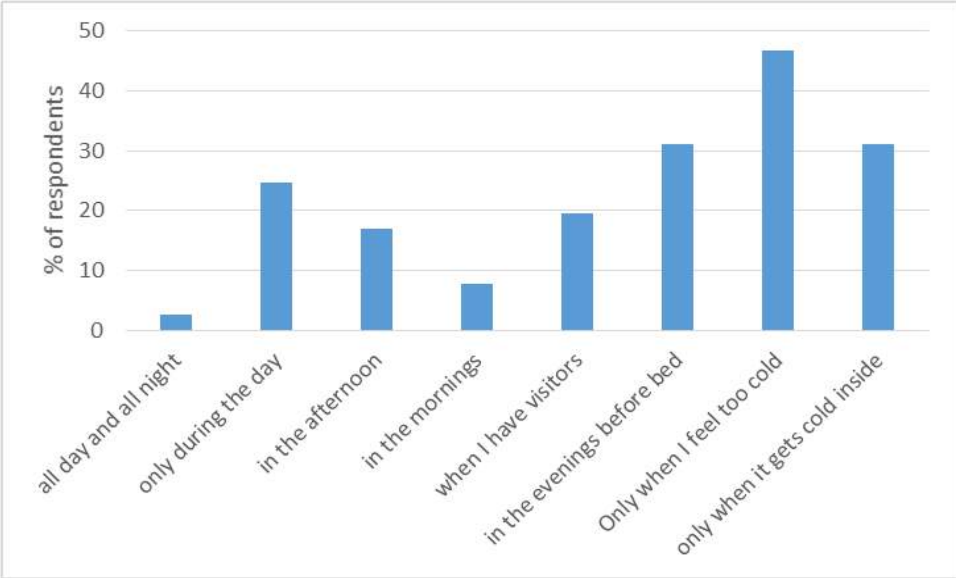


Figure 3 Heater use

4.2. Field Study

Participants in the field study were asked to indicate their thermal comfort with three different comfort measures; the ASHRAE 7-point Thermal Sensation Vote (TSV), the McIntyre 3-point thermal preference scale (TPV) and a simple thermal acceptability question, answering 'yes' or 'no' as to whether current conditions were thermally acceptable (TAV). This allows the neutral temperature to be calculated, but also for comfort ranges to be established according to the various measures.

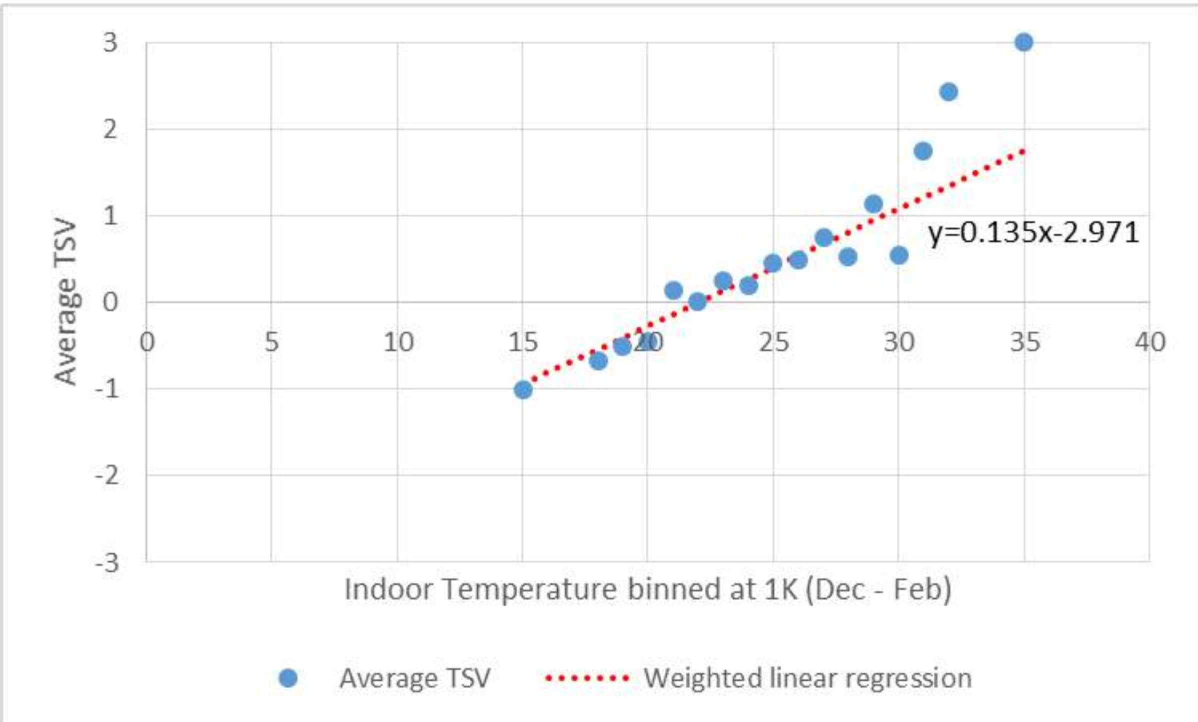


Figure 4 average TSV for each °C in summer months (Dec – Feb)

Figure 4 shows the relationship between TSV and the indoor temperature binned at 1K intervals for the summer months (Dec – Feb). Figure 5 shows the similar results for the winter months (Jun – AUG). The slope of the regression lines is taken to indicate the occupants' sensitivity to temperature variations. That is, the steeper the line the more sensitive or less tolerant to change of the indoor conditions of the cohort. This results show that the occupants in this study are much more sensitive to changes in the winter period. Weighted linear regression analysis give a neutral (TSV = 0) temperature of 22.0°C in summer and 19.7°C in winter.

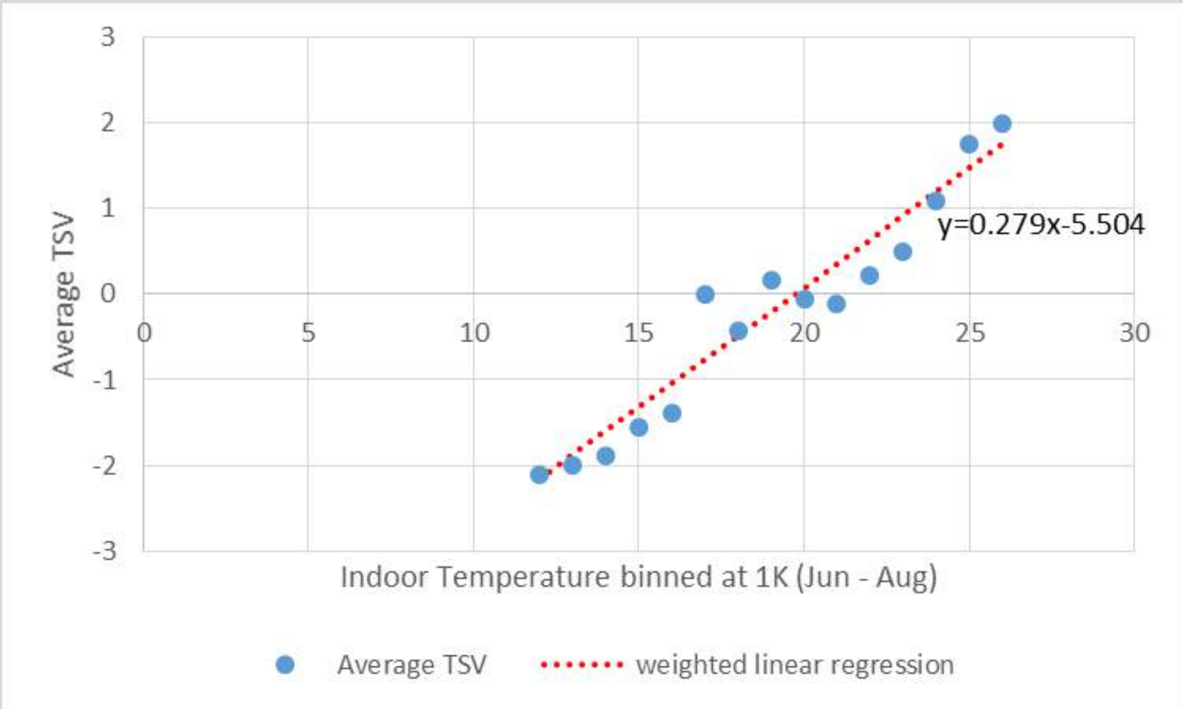


Figure 5 average TSV for each °C in winter months (Jun --- Aug)

4.3. Preference for Change

Three different measures of thermal comfort were examined by the field study. Comparing these measurements shows that there are differences between the different measures of acceptability; a neutral vote does not necessarily indicate an acceptable vote or that a participant desires no change in conditions.

To examine the differences between these measures of thermal comfort, qualifying data were plotted into a psychrometric chart and compared with the ASHRAE-55-2013 standard.

Votes were deemed to qualify for inclusion if the criteria set by the ASHRAE-55-2013 standard (ASHRAE 2013) were met: clothing of between 0.5 and 1 clo and a met rate of between 1 and 1.3.

When assuming the three central thermal sensation votes on the ASHRAE 7-point scale as 'acceptable', votes fall outside of the comfort zone indicated in red 27% of the time (Figure 6). When the TPV was zero, indicating no preference for change in thermal conditions, votes fell outside the comfort zone 25% of the time (Figure 7). When considered conditions to be thermally acceptable, votes fell outside the comfort zone 29% of the time (Figure 8).

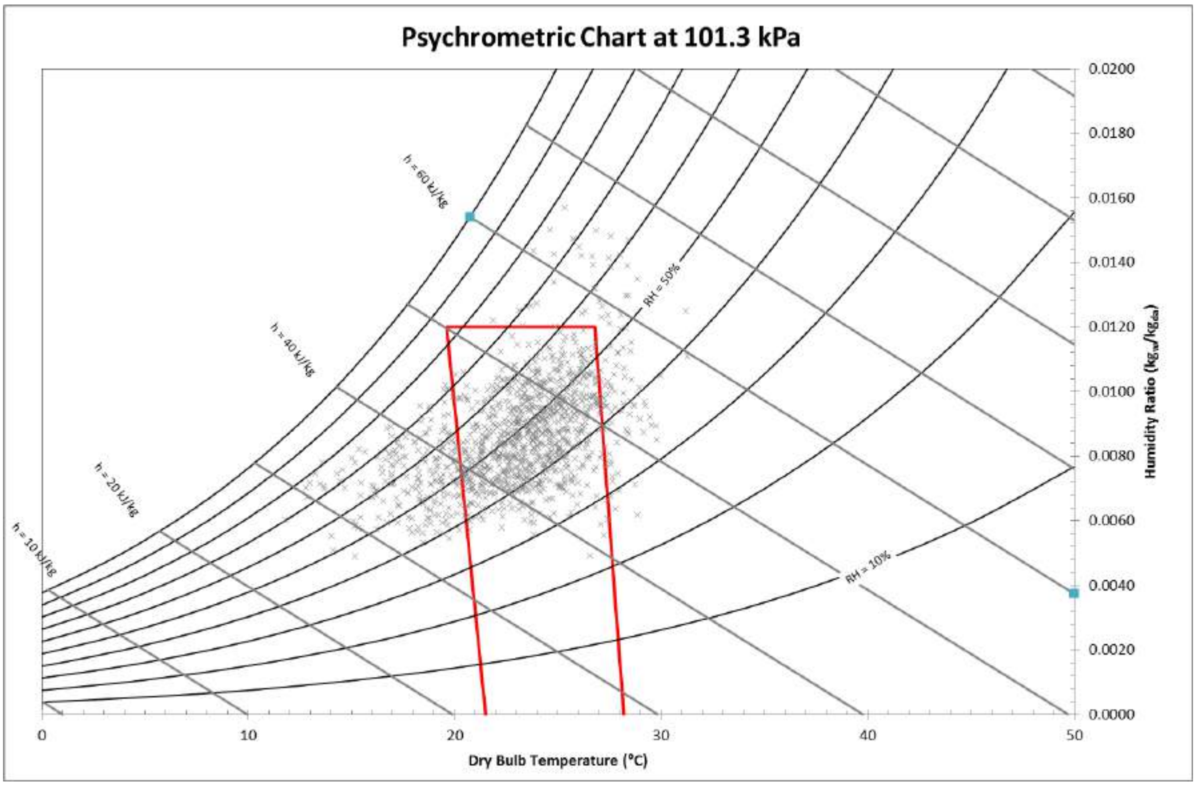


Figure 6 Psychrometric chart of the temperature and humidity at TSV vote -1, 0 and +1 on 7-point scale, clothing 0.5-1.0 CLO, activity level 1.0-1.3 MET *(red lines indicate the acceptable range of operative temperature and humidity according to ANSI/ASHRAE 55-2013 – 1.0/0.5 CLO zones merged)*

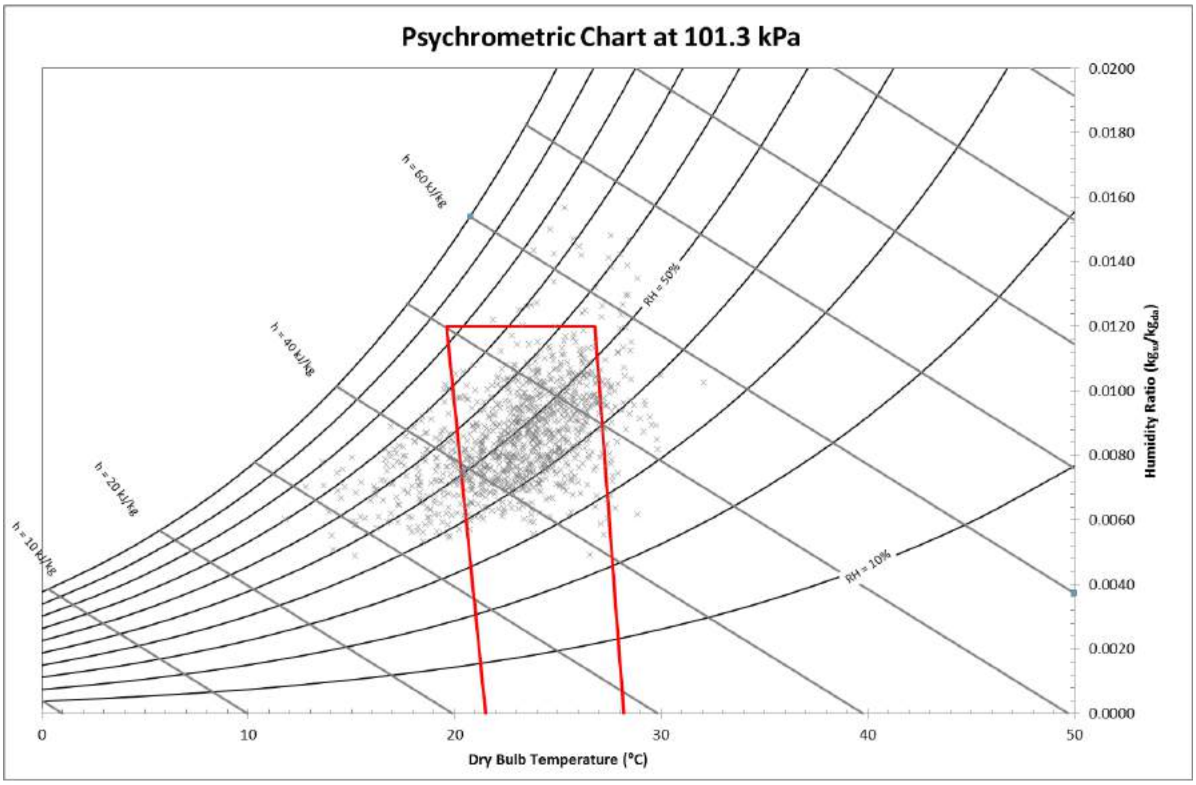


Figure 7 Psychrometric chart of the temperature and humidity at preference for no change on the McIntyre 3-point thermal preference scale, clothing 0.5-1.0 CLO, activity level 1.0-1.3 MET *(red lines indicate the acceptable range of operative temperature and humidity according to ANSI/ASHRAE 55-2013 – 1.0/0.5 CLO zones merged)*

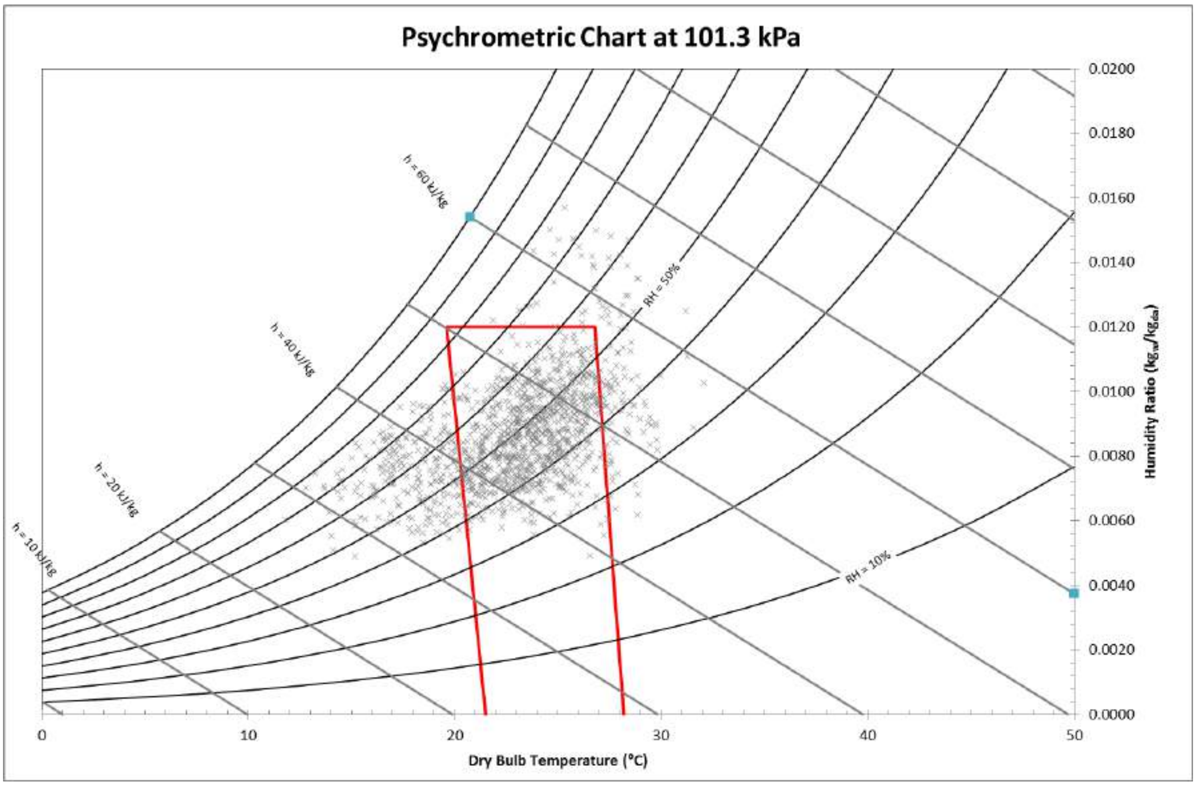


Figure 8 Psychrometric chart of the temperature and humidity when TAV was acceptable, clothing 0.5‐1.0 CLO, activity level 1.0‐1.3 MET *(red lines indicate the acceptable range of operative temperature and humidity according to ANSI/ASHRAE 55‐2013 – 1.0/0.5 CLO zones merged)*

Whilst votes fall outside of the comfort zone both to the left (indicating votes at cooler temperatures) and to the right (indicating votes at warmer temperatures), a greater number fall on the cooler side Table 1. In each case, 66% of the votes outside of the comfort zone are on the cooler side.

Table 1 Percentages of votes inside and outside of the ASHRAE‐55‐2013 comfort zone

	TSV	TPV	TAV
Within Comfort Zone	**73.3%**	**75.9%**	**71.3%**
Outside Comfort zone	**26.7%**	**24.1%**	**28.7%**
Cooler than comfort zone	**17.7%**	**16.0%**	**18.8%**
Warmer than comfort zone	**9%**	**8.1%**	**9.9%**

In Figure 9, TSV is compared with an unacceptable TAV and a TPV≠0 indicating a preference for change. The curves of the quadratic functions fitted to these variables have a minimum that falls slightly left of a TSV of 0. (Figure 9). Overall this indicates a greater acceptability of cool and cold TSVs than warm and hot, and slightly higher likelihood of a preference for change at positive TSVs than at negative ones, and thus a more frequent indication of a preference to be cooler rather than warmer.

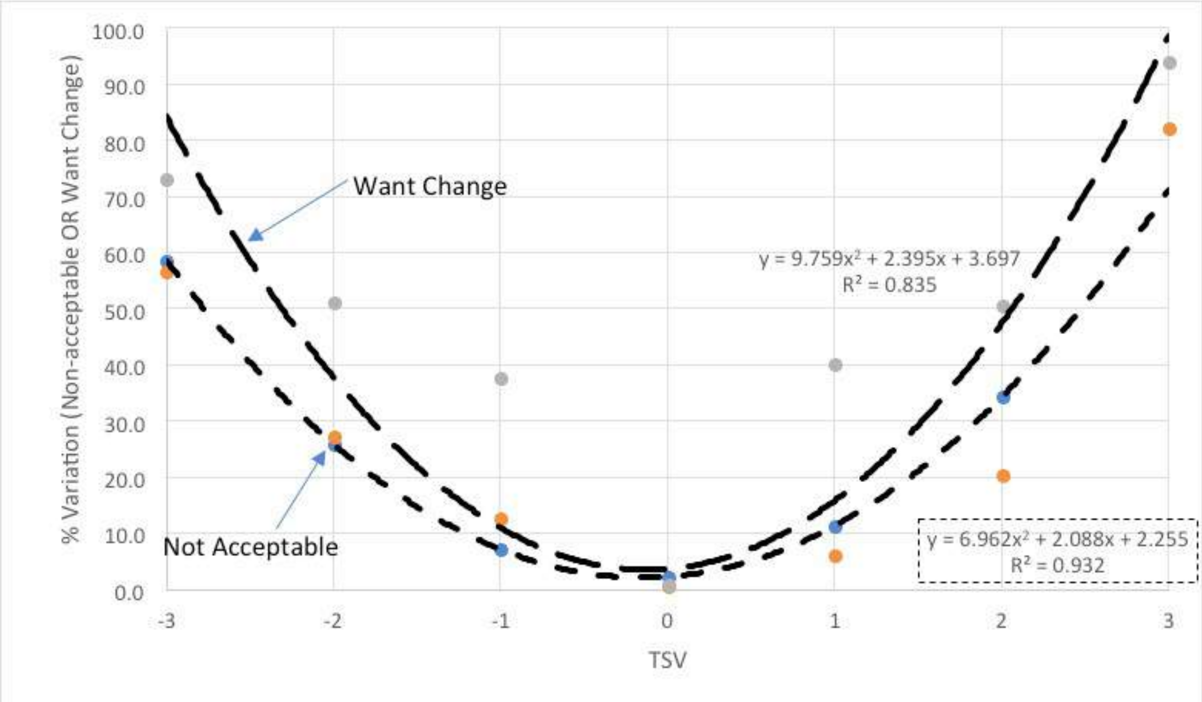


Figure 9 Preference for Change and Unacceptable thermal conditions compared with TSV

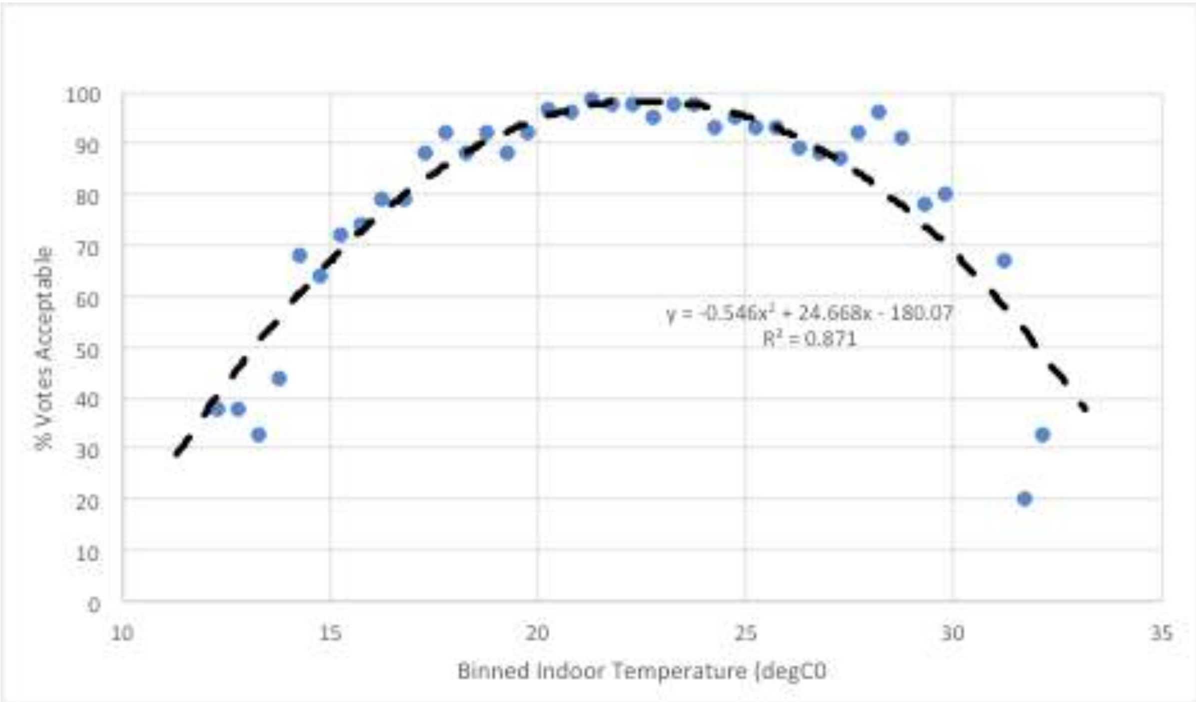


Figure 10 Acceptable votes by binned indoor temperature

When participants were asked whether conditions were acceptable, as opposed to indicating their current sensation or desire for change, the range of conditions was wider and more votes fell outside of the ASHRAE-55 comfort zone. There are times when conditions are deemed 'acceptable' but the participant still indicated a preference for change. Whilst it may seem a simple exercise in semantics, in the older population it is important to consider the conditions that will be 'accepted' or 'tolerated' as well as the conditions that are preferred or considered neutral. A reluctance to use heating and cooling appliances has been previously discussed amongst older residents of South Australia (Hansen et al. 2011), with local government officials reporting older people refusing to turn on air-conditioning due to the cost and behaviours linked with past resilience and ability to survive without the 'luxury' of heating and air conditioning. This may be linked to the wider range of conditions that are 'acceptable' to older people; these are conditions that can be 'put up with' despite the preference to be cooler or warmer.

In order to determine a range of acceptable temperatures for this cohort, the percentage of acceptable votes was binned by 0.5K intervals, as shown in Figure 10.

The maximum acceptability as determined by the equation of the line is 98.5%, occurring at 22.59°C. This is slightly higher than the summer neutral temperature, which is unsurprising given the TAV consistently gives a wider range of acceptable temperatures than either TSV or TPV. The trendline through this data was further extrapolated to determine the ranges of 80% and 90% acceptability (Table 2).

Table 2 Range of acceptable temperatures for 80% and 90% acceptability

	Low (°C)	High (°C)	Width (°C)
80% Acceptable	16.77	28.4	11.63
90% Acceptable	18.64	26.53	7.89

There are several trends across this thermal comfort data. Firstly, participants overall had a lower neutral temperature in winter than in summer. Their experience of the thermal environment shifted and they were less tolerant to changes in the temperature than in the summer months, as indicated by the slope of the weighted regression lines (Figures 3&4). Despite this, participants are more likely to report feeling thermally comfortable and find conditions acceptable at cooler temperatures than predicted by the ASHRAE-55 standard.

4.4. Overall health

During the study period, 256 votes reported symptoms which is equal to 9.6% of the total comfort vote forms returned. The breakdown of these symptoms can be found in Table 3.

Of these symptoms, 160 were reported by participants with chronic symptoms; those who reported symptoms in every vote were excluded to gain a clearer picture of the effects of temperature and thermal comfort on presentation of thermally symptoms.

Table 3 Breakdown of total symptoms reported by type

Headache	19
Dizziness	9
Racing Heart	2
Unexplained Tiredness	25
Coughing	13
Joint Pain	76
Sleeplessness	100
Other	12
Total	**256**

4.5. Thermal Conditions and Health

To determine the impact of the thermal environment on the health of the participants, the presentation of symptoms was compared with both the thermal sensation of the occupant and the temperatures recorded in the home.

First to be considered was the relationship between TSV and the presence of symptoms in otherwise healthy participants. The percentage of votes with symptoms at each point on the 7-point comfort scale was determined and graphed (Figure 11), with results weighted according to the total number of votes for each TSV.

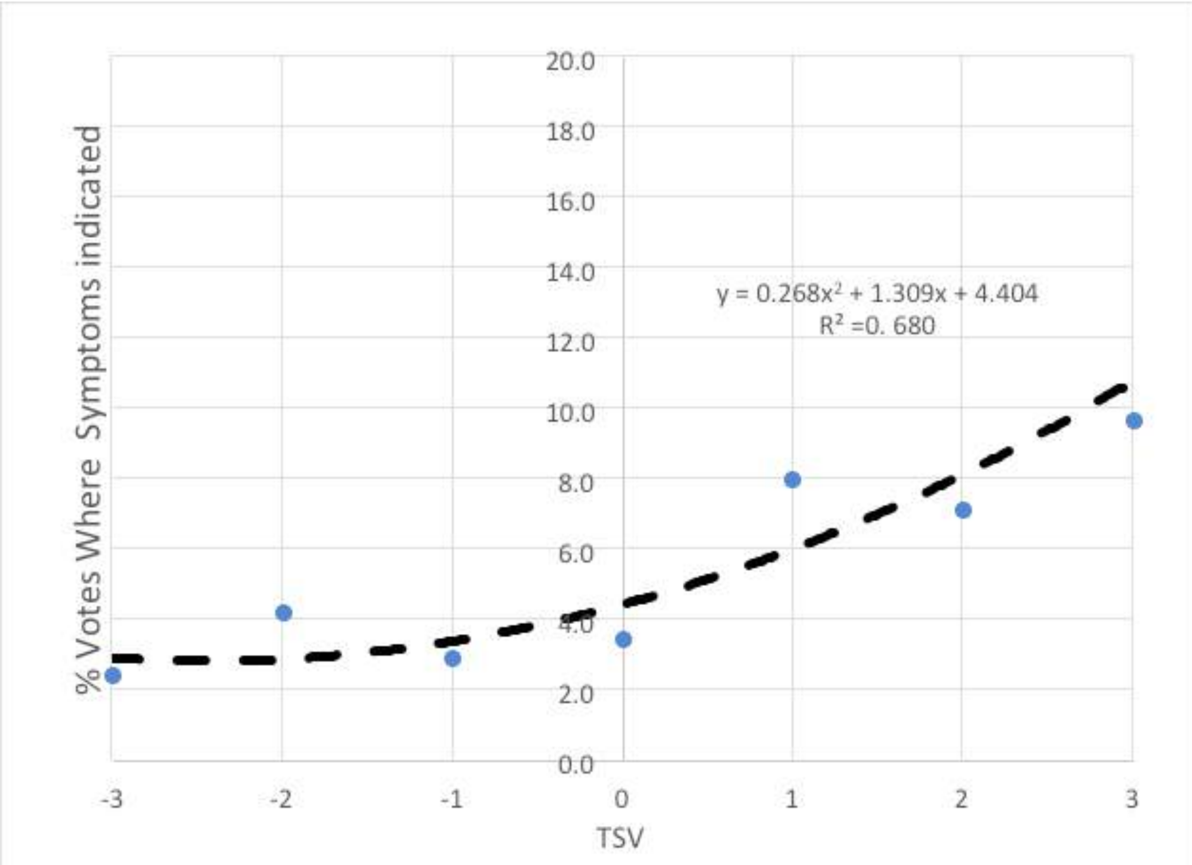


Figure 11 Percentage of votes where symptoms were reported at each thermal sensation vote score amognst otherwise healthy participants

In participants who did not present with chronic symptoms, TSV was related to the frequency at which symptoms occurred and that the relationship is represented by a quadratic function (Figure 11). Regression analysis showed that this relationship was significant ($p<0.01$). A greater number of symptoms were reported when positive TSVs were indicated than when negative TSVs were indicated suggesting a greater number of symptoms being reported during hot indoor conditions.

The comfort vote survey asked specifically whether symptoms had occurred within the previous 24 hours. For this reason, the percentage of symptoms at each 1 degree Kelvin of the minimum and maximum indoor temperature for the previous day were plotted (Figure 12). This measurement, rather than the temperature at the time that the vote was cast, gives a more accurate representation of the effect of temperature over time on the health of the occupants.

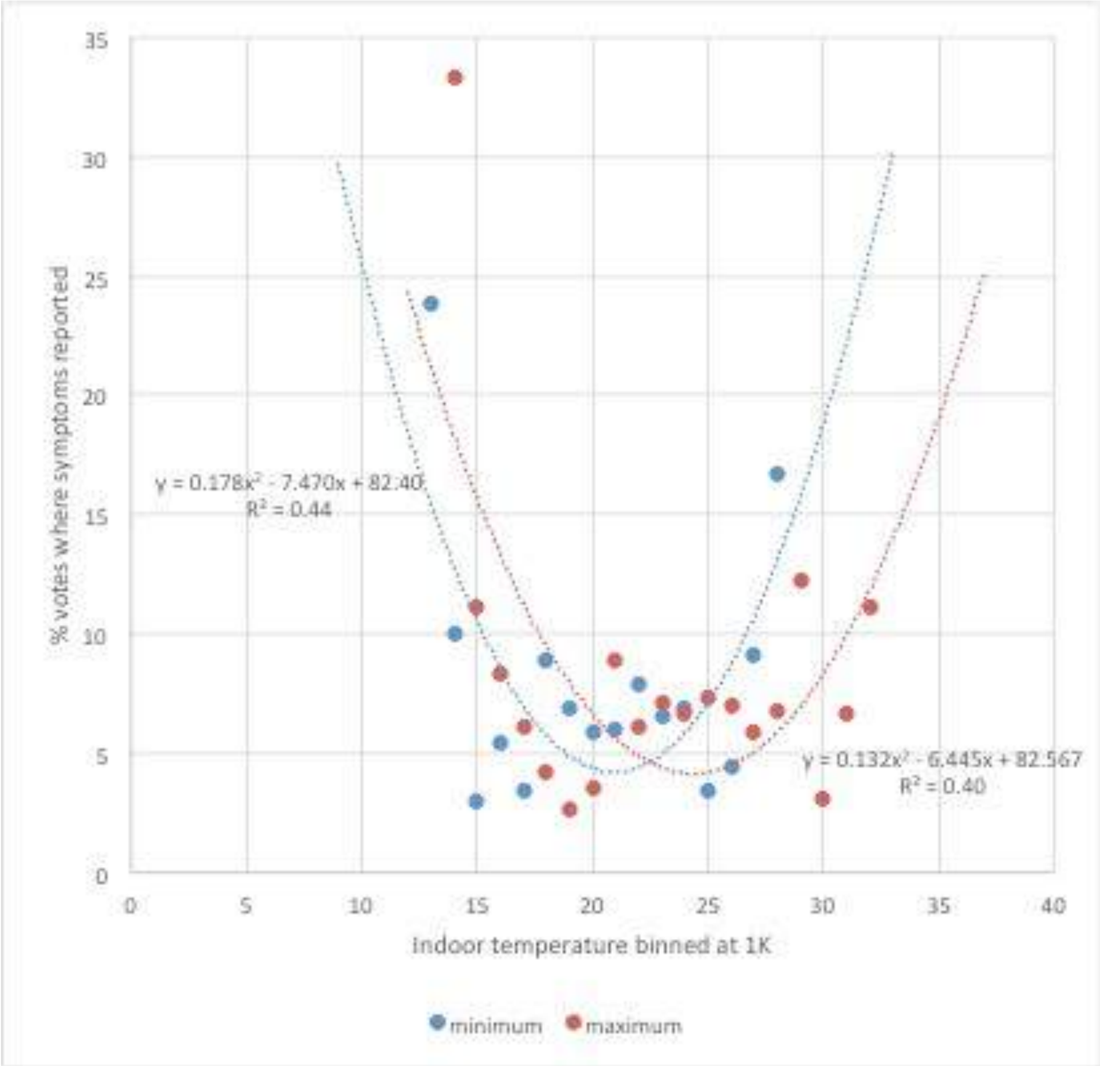


Figure 12 percentage of votes with symptoms amongst otherwise healthy participants at binned maximum and minimum °C for the previous day

This shows that the temperatures over the previous 24 hours have an influence on the number of symptoms experienced, with regression analysis showing these results to be significant for each variable ($p<0.05$). Overall this indicated that participants were more likely to suffer symptoms at extremes of temperature, with hot and cold maximum and minimum temperatures both related to an increased incidence of the reporting of symptoms.

The lowest point on the binomial curve in these graphs indicates the temperature, whether minimum or maximum, at which the fewest number of symptoms is predicted to occur. The lowest point on the 'minimum' equation is 21°C, whilst the lowest point on the 'maximum' curve is 24.3°C. This suggests a theoretical range of temperatures that should then be aimed at in the homes of older people to minimise the presence of symptoms. Of note is the fact that the safest minimum temperature is higher than the neutral temperature for this cohort in winter; this indicates that during colder months older people may not be keeping their houses adequately warm due to their own thermal preferences and behaviours.

4.6. Comfort Range vs Healthy Environment

The TAV consistently gives a wider range of temperatures that this cohort will find comfortable than TSV or TPV. Given the notion that older people may 'put up with' conditions they would prefer to change, this measure has been chosen to compare with the data regarding the presentation of symptoms.

Figure 13 below shows the quadratic functions fitted to the maximum (red) and minimum (blue) temperatures. The area shaded in green shows the range between the lowest point of each curve, which is a suggested range for reducing the presence of symptoms amongst older people. The area shaded in blue shows the range of conditions that would be deemed acceptable by 90% of participants.

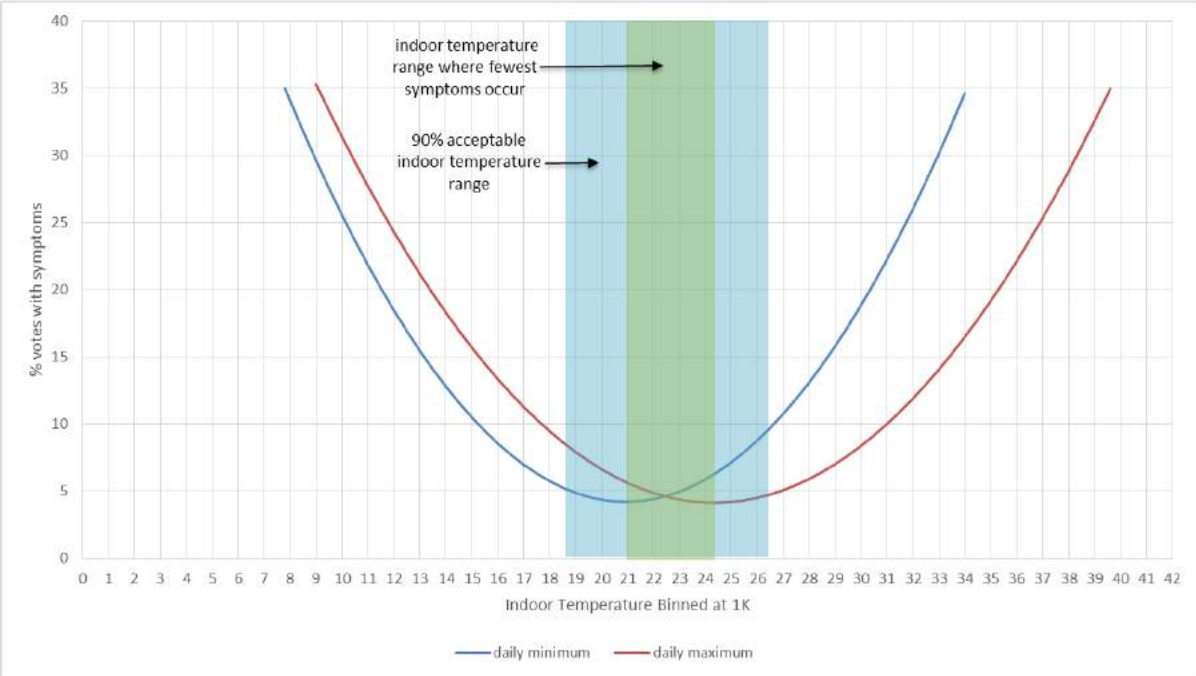


Figure 13 The quadratic functions of the trends of presentation of symptoms at daily minimum (blue) and maximum (red) temperatures. Shaded areas indicate the range of temperatures which would minimise the presence of symptoms (green) compared with the range of temperatures 90% of participants would find acceptable (blue).

This suggests that older people may be accepting of, and thus living with, conditions which may be associated with a greater risk of heat and cold related symptoms. However, the two ranges do overlap, so that most people would find conditions acceptable if they were within the green range indicated above. If there is a reluctance amongst this cohort to use their heating and cooling appliances as suggested by the study by Hansen et al (2011), there is an argument to be made for a program of housing improvement to use passive measures to bring the temperature range inside a house closer to that indicated by the green shading above.

5. Discussion

Up until recently, discussions around temperature and health within the Australian context typically revolved around heatwaves and the risks associated with extreme heat, especially given the predicted increase in such conditions as a result of climate change. This has shifted somewhat into an examination of cold related death and illness; despite mild winters there are surprisingly high numbers of death from cold related causes especially in comparison to Europe and America where winters are much colder (Bright et al. 2014). It has been suggested by public health researchers that this may be due to a lack of preparedness for cold; that clothing and housing utilised by Australians is not sufficient to maintain healthy winter temperatures (Barnett et al. 2017). This study has shown that it does not take very cold temperatures to being to see an increase in symptoms, and that anything below a minimum of 21 degrees is associated with increasing presence of symptoms. Given that the participants in the study had a neutral temperature lower than this in winter, it is thus a concern that winter heating practices, while seemingly providing acceptable thermal comfort, may not be providing the best environment for the promotion of good health.

It also shows that overheating is still of concern with high indoor maximum temperatures also being associated with increased numbers of symptoms. The relationship between the number of symptoms and positive TSVs, indicating a greater number of symptoms during warmer indoor conditions is also a concern, particularly for those who are unable to keep their houses cool during hot weather.

What is interesting about the results presented in this study is that the relationships are parabolic; symptoms increase with warmer minimum temperatures as well as colder temperatures. This phenomenon has been observed during heatwaves in Australia and worldwide; increases in morbidity and mortality are often during extended hot periods when night-time maximum temperatures remain high and there is no relief from high temperatures (Nicholls et al. 2008). Many participants in this study reported that they did not use any HVAC systems during the night; during hot nights in summer this means if natural cooling is not possible due to high outdoor temperatures, there will be no relief from hot conditions and this may lead to health problems.

The information collected in this study is a small sample however the trends seen suggest that indoor conditions are indeed linked to the presence of symptoms and that improvements to housing in South Australia may be a valid preventative health strategy. Similar strategies have been implemented in other countries and have been shown to be correlated with improved health amongst occupants (Thomson et al. 2009). These programs have primarily focussed on winter conditions; what remains to be seen is whether creating houses that are not just warmer in winter but also cooler in summer can help to also prevent heat related symptoms. Housing improvement programs have the added benefit of improving energy efficiency and potentially decreasing expenditure on energy costs, which for some older people and other vulnerable groups may have additional benefits, as energy poverty in Australia has also been linked to poor health outcomes (Chester & Morris 2011). Further study into the relationship between housing performance, energy efficiency and health are warranted to determine the potential efficacy of housing improvement as a preventative health strategy into the future.

6. Conclusion

This study has shown a relationship between indoor conditions and the presence of symptoms in otherwise healthy people over the age of 65. This relationship exists between both the indoor minimum temperature and the indoor maximum temperature and is binomial, and thus the presence of symptoms was related to both high and low temperatures. There was also a quadratic polynomial relationship between TSV and the presence of symptoms, with the fewest symptoms being reported when the TSV was slightly cooler than neutral. The relationship between indoor conditions, acceptability of these conditions and the frequency of symptoms presents an opportunity to explore the potential of housing improvement as not just a way of improving thermal comfort but also as a preventative health measure.

7. Acknowledgements

The author acknowledges the assistance of Terence Williamson in the production of some of the graphics for this paper.

8. References

ASHRAE 2013, ANSI/ASHRAE standards 55-2013, thermal environmental conditions for human occupancy, ASHRAE, Atlanta, GA.

Barnett, AG, Stewart, I, Beevers, A, Fraser, JF & Platts, D 2017, 'Thermal clothing to reduce heart failure morbidity during winter: a randomised controlled trial', BMJ Open, vol. 7, no. 10.

Bills, R 2016, 'Cold Comfort: Thermal sensation in people over 65 and the consequences for an ageing population', Proceedings of 9th Windsor Conference: Making Comfort Relevant, Network for Comfort and Energy Use in Buildings.

Bright, FM, Winskog, C, Walker, M & Byard, RW 2014, 'A Comparison of Hypothermic Deaths in South Australia and Sweden', Journal of Forensic Sciences, vol. 59, no. 4, pp. 983-985.

Chester, L & Morris, A 2011, 'A new form of energy poverty is the hallmark of liberalised electricity sectors', Australian Journal of Social Issues, vol. 46, no. 4, pp. 435-459.

Commonwealth of Australia 2015, 2015 Intergenerational Report: Australia in 2055, Commonwealth of Australia, Canberra.

Critchley, R, Gilbertson, J, Grimsley, M & Green, G 2007, 'Living in cold homes after heating improvements: Evidence from Warm-Front, England's Home Energy Efficiency Scheme', Applied Energy, vol. 84, no. 2, pp. 147-158.

Dufour, A & Candas, V 2007, 'Ageing and thermal responses during passive heat exposure: sweating and sensory aspects', European Journal of Applied Physiology, vol. 100, no. 1, pp. 19-26.

Fanger, PO 1973, 'Assessment of man's thermal comfort in practice', Occupational and Environmental Medicine, vol. 30, no. 4, pp. 313-324.

Government of South Australia 2017, The 30 year plan for Greater Adelaide, Government of South Australia, Adelaide.

Hansen, A, Bi, P, Nitschke, M, Pisaniello, D, Newbury, J & Kitson, A 2011, 'Perceptions of Heat-Susceptibility in Older Persons: Barriers to Adaptation', International Journal of Environmental Research and Public Health, vol. 8, no. 12, pp. 4714-4728.

Howden-Chapman, P 2004, 'Housing standards: a glossary of housing and health', Journal of Epidemiology and Community Health, vol. 58, no. 3, pp. 162-168.

Hwang, RL & Chen, CP 2010, 'Field study on behaviors and adaptation of elderly people and their thermal comfort requirements in residential environments', Indoor air, vol. 20, no. 3, pp. 235-245.

Indraganti, M 2011, 'Thermal comfort in apartments in India: Adaptive use of environmental controls and hindrances', Renewable Energy, vol. 36, no. 4, 2011/04/01/, pp. 1182-1189.

Koskela, HO 2007, 'Cold air-provoked respiratory symptoms: the mechanisms and management', International journal of circumpolar health, vol. 66, no. 2, pp. 91-100.

Natsume, K, Ogawa, T, Sugenoya, J, Ohnishi, N & Imai, K 1992, 'Preferred ambient temperature for old and young men in summer and winter', International journal of biometeorology, vol. 36, no. 1, March 01, pp. 1-4.

Nicholls, N, Skinner, C, Loughnan, M & Tapper, N 2008, 'A simple heat alert system for Melbourne, Australia', International Journal of Biometeorology, vol. 52, no. 5, pp. 375-384.

Nitschke, M, Hansen, A, Bi, P, Pisaniello, D, Newbury, J, Kitson, A, Tucker, G, Dal Grande, E & Avery, J 2014, Adaptive capabilities in the elderly during extreme heat events in South Australia, SA Health, Adelaide.

Nitschke, M, Tucker, GR & Bi, P 2007, 'Morbidity and mortality during heatwaves in metropolitan Adelaide', Med J Aust, vol. 187, no. 11-12, pp. 662-665.

Schellen, L, van Marken Lichtenbelt, W, Loomans, M, Toftum, J & De Wit, M 2010, 'Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition', Indoor Air, vol. 20, no. 4, pp. 273-283.

Sturman, AP & Tapper, NJ 2006, Weather and climate of Australia and New Zealand, Oxford University Press.

Thomson, H, Thomas, S, Sellstrom, E & Petticrew, M 2009, 'The health impacts of housing improvement: a systematic review of intervention studies from 1887 to 2007', American journal of public health, vol. 99, no. S3, pp. S681-S692.

Wilkinson, P, Pattenden, S, Armstrong, B, Fletcher, A, Kovats, RS, Mangtani, P & McMichael, AJ 2004, 'Vulnerability to winter mortality in elderly people in Britain: Population based study', British Medical Journal, vol. 329, no. 7467,

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Health Responses of Acclimatized Construction Workers in Summer Season with high ambient temperature: A case study in Chongqing, China

Sadia Yasmeen [1,2], Hong Liu[1,2*], Chen Lu[1,2] and He Jiaze[1,2]

[1] Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing 400045, China.
[2] National Center for International Research of Low-carbon and Green Buildings (Ministry of Science and Technology), Chongqing University, Chongqing 400045, China.

Abstract: Heat stress and labor health are two most concerning matters in the construction field. The objectives of our research were to observe physiological responses of construction workers during hot summer and identify the worker heat tolerance level. Environmental parameters together with workers (10 subjects) physical responses (i.e. heart rate, skin temperature) were collected. Labors avoided work during the hottest period of a day (appx. 10:30 A.M. to 3:30 P.M.). Therefore, they worked continuously without felt fatigue though in some cases WBGT was higher than the normal limit and with a high workload. Workers heat tolerance level was found to be good because all of them were local people and acclimatized with the hot weather for at least 7 years. The workers resting time heart rate ranged from 58-87bpm. Natural wind and artificial wind (fan) were used as cooling methods at the end of each day work for 15 minutes' rest time (on-site shaded place). Under artificial wind, skin temperature gradually decreased on average 1°C but in natural ventilation, the result fluctuated. Heart rate in both conditions decreased around 15-20 bpm within 2-3 minutes and then remained almost steady. Our study suggests that a labor-friendly work schedule may reduce labor heat stress.

Keywords: Heat stress, outdoor environment, acclimatized, metabolic rate, construction worker, work-schedule.

1. Introduction

Global temperature is predicted to be increased gradually in coming year, therefore it is also expected that heat-related mortality will be increase than ever before (INABA, KUROKAWA and MIRBOD, 2009). Work under direct sun exposure is one of the main cause of making the outdoor worker more vulnerable with high work intensity (XIANG *et al.*, 2014) but if they are acclimatized then this probable risk might be less than non-acclimatized worker (Périard, Racinais and Sawka, 2015).

The average ambient temperature is gradually increasing caused by the climate change. In Asia, the temperature is rising about 0.14°C to 0.20°C in every ten years since 1960s (Hijioka et al., 2014). About 0.84°C was increased in last century and is still increasing (Hondula et al., 2012). As a consequence of climate change, the mean annual temperature is increased (IPCC, 2013) and heat wave will be more frequent than ever before (Dunne et al., 2013).

Both indoor and outdoor worker's health are affected by this increasing temperature. In 2100 the average temperature will be increased to 3°C (Kjellstrom et al., 2009). Productivity and working ability will be reduced because of this increasing temperature and which may lead to decrease the world GDP (Kjellstrom et al., 2016). Under this circumstance, labor health will be a critical factor.

Thermal comfort, health responses and human performance inextricably linked with each other. A large number of researchers (Grether, 1973; Ramsey and Morrissey, 1978; Kobrick and Fine, 1983) studied on human performance in different thermal conditions while Wing (1965) was the pioneer and had a huge contribution on this field (Ramsey, 1995), but in Chongqing only a few studies were conducted in previous years. Chongqing is one of the fast-growing city in China with around 30.1 million populations where 18.38 million live in the city area. Thousands of construction workers are involved to build a new city for the better living place and for a convenient and fast transportation system. However, only a few studies reported construction workers' physiological response during the hot summer season in Chongqing. In addition, accidental health hazards are frequently occurred due to its hot and humid summer condition, lack of knowledge about heat stress and absence of proper reflect of rules and regulations (XIANG *et al.*, 2014). In USA heat-related death especially in agricultural sector about 30 workers per year, a heat wave caused nearly 15000 death in France within 2 weeks in 2003, in Europe about 70000 death has been reported as a result of a heat wave (Kjellstrom *et al.*, 2016). Chinese newspaper report that last summer (2017) in Xi'an and Suzhou province about 4-5 people died due to work in an excessive hot weather in July.

The human body has different responses based on the thermal condition. Its responses are depended on the interaction of six factors such as air temperature, radiant temperature, humidity, air velocity, heat production (inside body) and also clothing insulation (Ken Parson (2003), Fanger (1970)). The performance of some mental tasks was decreased due to heat and the level was high during increased temperature with a long period of time (Ramsey, 1995). A recent study reported that if a worker takes 25% break from their effective working time and also work in an alternate pair way it would help to protect the worker from heat strain in a hot environment (Mairiaux & Malchaire, 2015).

Chongqing City is in the southwest part of China, which is characterized by very humid and hot in summer, the average temperature is about 38-40°C with around 60% humidity during the daytime. Such environmental conditions suit perfectly for the current research objectives. The main purpose of this study was to observe the physiological conditions of an outdoor construction worker, which may support to reduce heat-related worker injury in the construction field.

2. Methodology

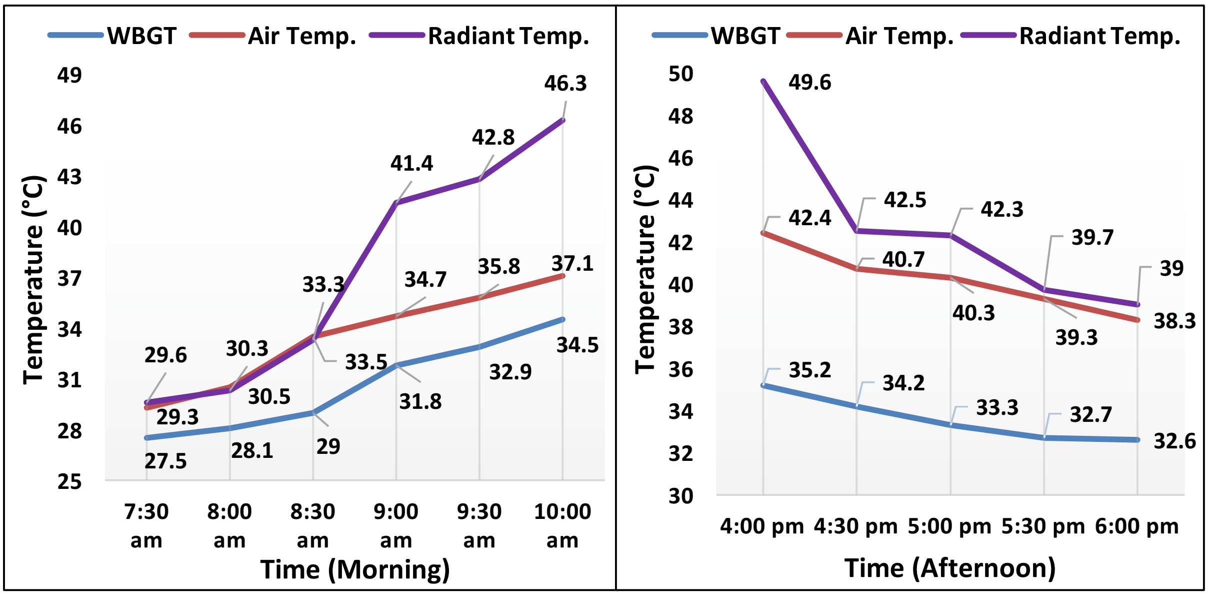
2.1. Brief of the field study

The study was conducted in a construction site in Shapingba district, Chongqing, China. Assumed 10 acclimatized subjects were randomly selected. Chongqing municipality situated in hot summer and cold winter zone in China. July and August are the hottest months in Chongqing. Subjects were involved in different tasks (Picture 1), in both conditions, indoor

Picture 1: Some onsite (indoor and outdoor) working pattern

(no direct sun exposure) and outdoor (direct sun exposure) conditions.

In this construction site, the worker did not have any fixed work schedule. Usually, they had two shifts morning and afternoon and the approximate time was 6:30 to 10:30 A.M. and 4:00 to 7:30 P.M. respectively. For outdoor worker (work direct sun exposure) this time could be changed, and they were also free to cancel their working shift based on temperature. The worker may stop their work if they feel so hot or uncomfortable. Indoor worker (work in a shaded place avoid direct sun exposure) such as wall maker, driller or griller they started work at afternoon around 3:30 P.M. We collect our data from afternoon shift because at morning high sunshine was observed in the studies site about 8:30 to 9:00 A.M. and the morning weather also influenced by the previous night. Figure 1 represents one random day temperature difference between two different working shifts prior to main data collection, that helped to understand which shift was hottest one and for how long.



(A) (B)

Figure 1: Temperature differences between morning and afternoon working shift

In Figure 1 (A) gradual temperature increase is evident. At morning from 9:00 to 10:00 A.M. (last one hour in the morning shift) Wet Bulb Globe Temperature (WBGT) was around 31.5-34.5°C, where during afternoon session (Figure 1 (B)) (4:00 to 6:00 P.M.) it was near 35-32.5°C, in afternoon shift workers work in a hot environment for long period of time (more than 2 hours) compare to morning session working time of the day. In morning direct sunlight come to the sample site around 9:00 A.M. and available until 6:30 P.M. Data was collected twice (two different days) from each sample in two different cooling systems (natural and artificial wind) on two days.

2.2. Environmental parameters measurement

The study was conducted during the hottest summer months in Chongqing, at the end of the July to mid-August. The environmental parameters were measured by using onsite devices, including WBGT (Equation 1,2), air temperature, air velocity and radiant temperature. Table 1 shown name of the devices with accuracy and ranges that was used to collect data. Relative humidity was collected from the nearest local weather station. Physical responses of workers in the hot environment were also measured including heart rate, skin temperature, core temperature, blood pressure and clothing insulation. To calculate metabolic rate (Equation

4), WBGT, core temperature (Equation 6) and cloth insulation, ISO8996, ISO7243, ASHRAE HANDOOK (2009) and ASHRAE 55 was used. Sweating rate was calculated using ISO 7933, (Equation 5) and equations are given below.

ISO 7243 (WBGT equation):

$$WBGT\ (with\ solar\ load) = 0.7t_{nw} +\ 0.2t_g + 0.1t_a \quad (1)$$

$$WBGT\ (without\ solar\ load) = 0.7t_{nw} + 0.3t_g \quad (2)$$

Whereas $\mathbf{t_{nw}}$ is natural wet bulb temperature, $\mathbf{t_g}$ is the globe temperature and $\mathbf{t_a}$ is air temperature.

$$WBGT_{eff} = 34.9 - (\frac{M}{46}) \quad (3)$$

$WBGT_{eff}$ = The Time Weighted Average effective WBGT (effects of heat to work in a long period of time in different metabolic rates).

M = Metabolic rate.

ISO 8996 (Metabolic rate calculation):

$$HR = HR_0 + RM\ (M-M_0) \quad (4)$$

Here, HR = Heart rate

HR0 = is the heart rate at rest, under neutral thermal condition

M = is the metabolic rate, in watt per square meter

M0 = is the metabolic rate in rest, in watt per square meter

RM = is the increasing in heart rate, under per unit of metabolic rate.

ISO 7933 (Sweating rate):

$$SW_{max} = (M - 32)A_{Du} \quad (5)$$

SW_{max} = Maximum sweating rate

M = Metabolic rate

A_{Du} = Body surface area

Core temperature (2009, ASHERA Handbook):

$$M - W = (C + R + E_{sk}) + (C_{res}\ + E_{res}) + (S_{sk} + S_{cr}) \quad (6)$$

Where,

W = rate of mechanical work accomplished

M = rate of metabolic heat production

C + R = sensible heat loss from skin;

Esk = total rate of evaporative heat loss from skin.

Cres = rate of convective heat loss from respiration

Eres = rate of evaporative heat loss from respiration

Ssk = rate of heat storage in skin compartment

Scr = rate of heat storage in core compartment.

Table 1- Lists of instruments used for data collection.

Parameters		Instruments Name	Model	Range	Level of Accuracy
Environmental Parameter	Wet Bulb Globe Temperature (WBGT)	WBGT Thermal Index Device	JTR10A	1°C (50-120°C)	±0.5 (5-50°C)
	Air Temperature				
	Radiant Temperature				
	Air Velocity	KIMO Instruments	KIMO 24621	0.15-3.00ms^{-1} and 3.1- 30ms^{-1}	±3% of reading 0.05ms^{-1} and ±3% of reading ±0.2ms^{-1}

Physical Parameter	Blood Pressure	Omron	U30	0-299mmHg(0-39.9KPa)	±3mmHg(±0.5KPa)
	Heart rate	Polar	A300	-10 °C to +50 °C / 14 °F to 122 °F	± 1% or 1 bpm
	Skin Temperature	Thermochron Temperature Logger	DS1922T	32°F to 257°F (0°C to 125°C)	±0.5°C
		Infrared Thermometer Gun	DT600	-20°C- 100°C	±2°C
	Core Temperature	Barun ThermoScan®	7 IRT6520	10 – 40 °C (50 – 104 °F)	±0.2 °C (±0.4 °F)

Here, a fan was used as a cooling device for 15 minutes resting time after day work.

All environmental parameters were collected in every 30 mins. Before measuring WBGT, the device was preset for about 30 mins. and 1 m above the ground. Other physiological parameters such as core temperature, skin temperature were collected before samples start working and when they finished work. Heart rate was measured continuously throughout each day working period. Physical parameters were collected at the five-minute interval for 15 mins. when the sample was in rest in a shaded place (in the construction site) with two conditions natural ventilation and fan, the distance between fan and sample was 1 m. Data from 2 subjects were collected per day.

A questionnaire survey was conducted, total 35 both structured and non-structured questions were included in the questionnaire to pick healthy samples and to understand their lifestyle with their perception of work in the hot environment. Maximum age group belongs to 40-60 years. About 70% of subjects had a smoking habit where the percentage was 40 for little drink alcohol and only one subject whose had both habits. In the field of construction, they all had 7-40 years' experience for working in Chongqing-like weather. Besides their working experience, all of them were Chongqing local people. Microsoft Excel 2016, R Environment and SPSS 22.0 is used to analyze the data.

3. Results and Discussion:

3.1. WBGT (Wet Bulb Globe Temperature)

The WBGT level was measured from closest area to the sample working place. Figure 2 shows the day wise (mean value of every sampling day in the afternoon shift) measured temperature distribution, while Figure 3 depicts the average value of environmental parameters (WBGT, air temperature, radiant temperature and air velocity) during the sampling periods at the afternoon shift. The daily average WBGT, air and radiant temperature were higher at the beginning afterward gradually decreased over time (Figure 3). Average decreasing level of WBGT was 2°C within around 3.5 hours (each day total sampling hours) (Figure 3). The maximum and minimum value of WBGT was 36.5°C and 27.4°C during the afternoon working session. The WBGT value was higher for 60% from the reference WBGT ($WBGT_{eff}$) value. In afternoon WBGT reached the level of reference value of WBGT worked after near about 2.5 hours or around 6:00 P.M. Previous study shown that, in a hot summer area morning time work with high WBGT and due to continue high workload the effective value of WBGT reach earlier than hot and humid condition (Bröde *et al., 2017*). A limited number of injuries are reported during 7:00 to 9:00 A.M. whereas most injuries are reported from 2.30 to 3.00 P.M. for a construction worker and every 1°C increasing of WBGT reduce 0.57% of work hour (Li *et al.*, 2016).

ISO 7243 referred a work-rest ratio for workers. Work-rest cycle would be 50-50 (1-hour basis) when local WBGT is 32-28.5°C with low-high work intensity. In this study, subjects worked continuously (average 2 hours) even at a high ambient temperature without no longer break. Drinking water was the common purposed to stop work just for a while, which is a very primary way to protect the body from hot weather. Among ten days sampling period, only 2 days two different subjects take more than 30 minutes breaks in total around 3 hours each, others were work almost continuously even though WBGT was high (more than 32°C). The ISO standard 7243 is used to estimate the hot environment based on the WBGT index. Both acclimatized and non-acclimatized worker and their good health are kept in concern. For an acclimatized worker with low metabolic rate (115W) the highest value of WBGT is 32.4°C whereas for non-acclimatized is 30.1°C. The lowest value is 23.5°C and 19.2°C with very high metabolic rate (520W) for acclimatized and non-acclimatized worker respectively. Zhao et al. (2009) reported that more than 34°C WBGT reduce the time of heat tolerance of subjects in a hot and high humid environment.

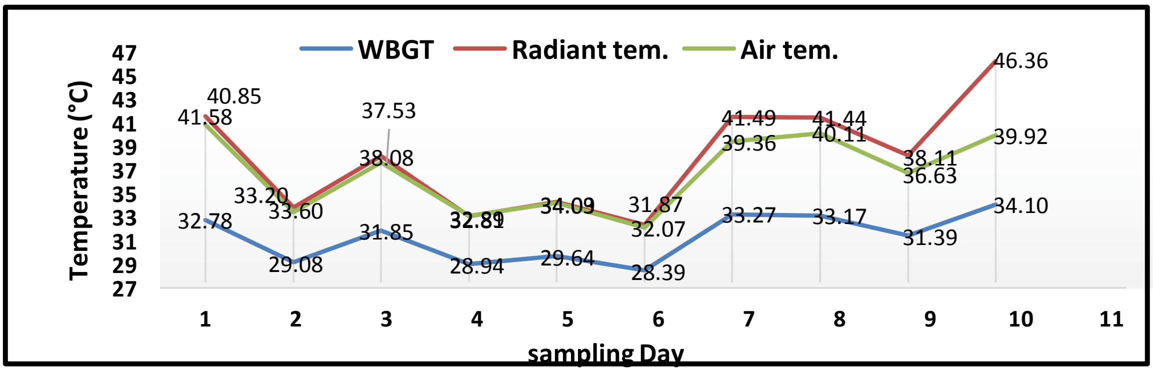


Figure 2: Mean WBGT, radiant temperature and air temperature during the field study

There were no other artificial heat sources around the study area, i.e. the adjacent environment was only influenced by nature. The study was conducted in outdoor environment therefore, relevant parameters were independent to change anytime, such as comparative high wind velocity than normal, sudden rain and or cloud cover.

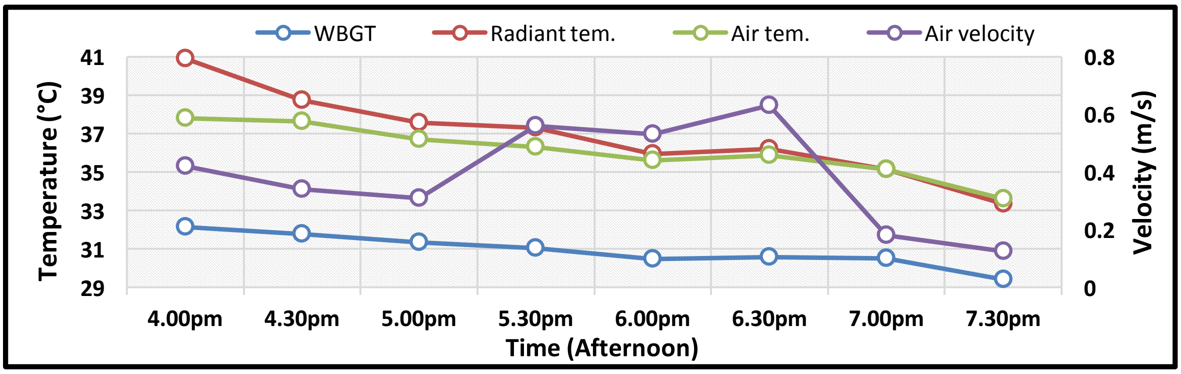


Figure 3: The average decreasing trend of three Environmental parameters related to human thermal response (WBGT, Radiant temperature and Air temperature) and air velocity over sampling time (afternoon).

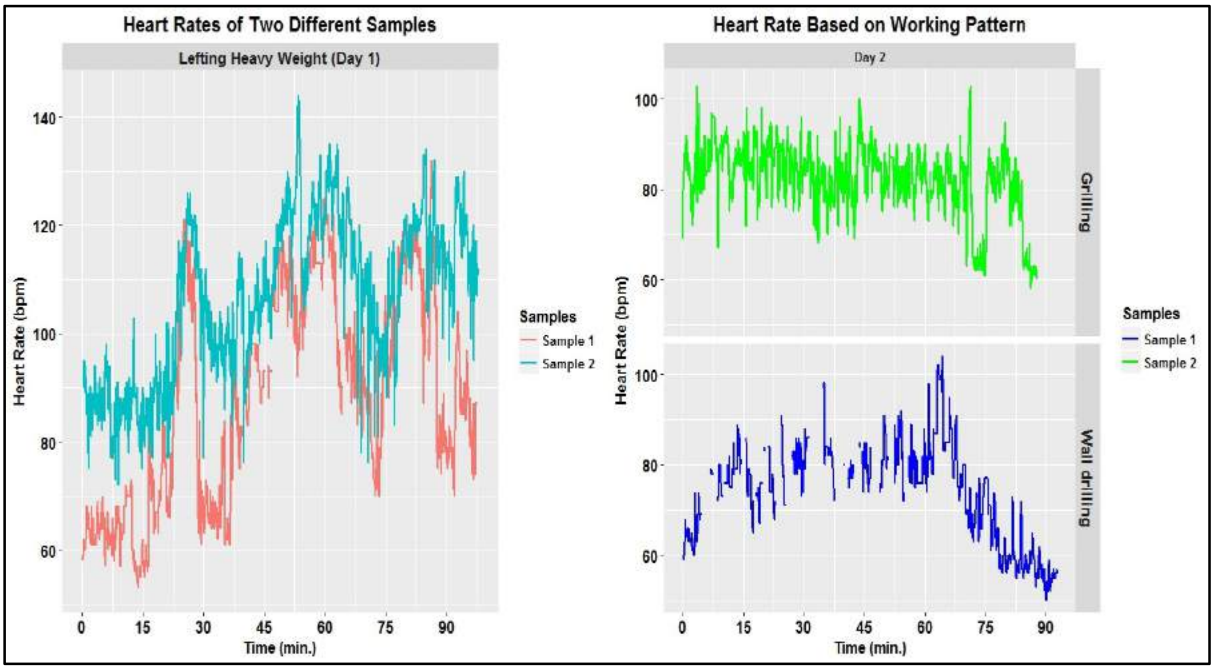
3.2. Metabolic rate

The workers in this construction site were involved in low to high workload. Workers metabolic rate generated by physical activities was varied from 84Wm^{-2} to 257Wm^{-2}, with 65% had a moderate workload and 30% high workload. The metabolic rate of building outsider wall driller was 84Wm^{-2} when outdoor average WBGT was 29°C and. Though WBGT was 29°C but the internal roof, wall and floor's temperature was high 42°C, 37°C and 36°C respectively. In this study, three categories of work pattern were belonging to moderate metabolic rate and these are, indoor wall construction workers, lifting heavy weight and drilling concrete outside the building. Outdoor wall construction workers, assist the wall construction worker (carrying sand and cement mixture, bricks to the wall construction workers) and drilling pillars under direct sun exposure was under high metabolic rate. Temperature patterns are changing due to climate change and it reduces work productivity 9% for moderate (around 160Wm^{-2}) workload and 25% for heavy (around 220Wm-2) workload in this rising temperature (*Cheung et al., 2016*). In the time of high WBGT (around 34°C) and work pattern together shifts metabolic rate from moderate to high, even though 60% workers' perception about their own workload was 'moderate'.

About 80% workers thought the environment was too hot for work with 70% feel fully wet skin, cloth stick to the skin surface and sweat loss from their body. Though worker feels very hot and humid, they didn't feel any severe fatigue during working time except little tired. Most of the worker feel excessive thirsty and only about 22% worker felt weak to work in such a hot environment. The worker did not take any break during working time except drinking.

3.3. Heart rate

In resting period workers heart rate was found within the range of 58- 86bpm, which is not under extreme threshold limit (90 or 100bpm) (Fox *et al.*, 2007 and Pittaras *et al.*, 2013) and indicates their physical fitness. Among 10 subjects two of them involved in lifting heavy weight (outdoor) their heart rate was found from 58 - 144bpm, the heart rate become high when they were lifting the weight and put them in a big box, this box was carried out by the crane. Worker had to wait until the box coming down at that time their heart rate was



(A) (B)

Figure 4: Heart rate on two different days (Day 1 and Day 2), two different working patterns.

decreased (Figure 4 (A)). The heart rate was increased about 60 to more than 120bpm, which takes about 15 minutes and to fallen down within 10 to 20 minutes. Increase and decrease hearts rates were varied with a different sample. In addition, next day the same subjects did two different work (Grilling and wall drilling). In this case, their heart rate was almost below

100bpm, the average heart rate (with standard deviation) was about 76±8.9 and 82±7.8bpm for wall drilling and grilling worker respectively, it is also difficult to collect uninterrupted data from the on-site worker (Figure 4 (B)). The differences in heart rate between two working patterns are in Figure 4. However, for indoor wall construction work both heart rate and WBGT was almost similar in two different sampling days (around 29°C) and air temperature (34°C) (Figure 5). In this case, increment and decrement limits of heart rate were about 50 bpm (near about 80 to 120bpm) from their rest time heart rate and other picks were just for few seconds. According to WHO upper limits of heart rate are 110bpm per min (World Health Organization, 1969).

The heart rate of outdoor wall construction worker was higher than the indoor wall construction worker (above 100 to below 140bpm) (Figure 6). The average heart rate of outdoor wall construction subjects was about 119 and 118 (2 subjects) where indoor workers were around 96±8.23 and 83±10.9bpm (two days' average of two samples heart rate). After about 12-15 min. the heart rate of outdoor wall construction worker was reached at an average high level of their working hour heart rate. For the person who has assisted wall construction workers (mixed sand-cement with water and carried out the mixture and bricks to the wall construction worker) two days' average heart rate was about 100bpm.

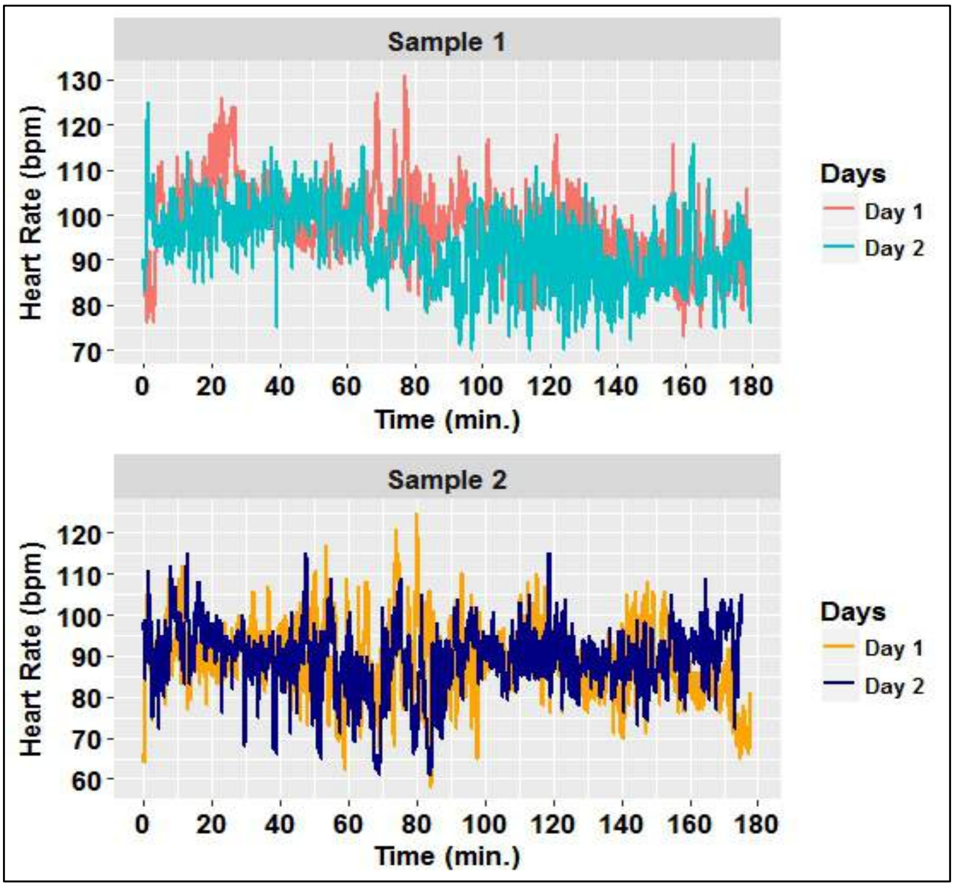


Figure 5: Similar Heart rate level in same working pattern (indoor wall construction worker)

Medical testing was developed for the new worker wants to join in South African mines, where heart rate limit is less than 160bpm in 28°C WBGT and 80W metabolic load for 30 mins. and for HAZMAT worker heart rate limit is about 100bpm with below 38.9 and 37.2°C core temperature, and it decreases the heat-related injury about 60% (Cheung *et al.,* 2016).

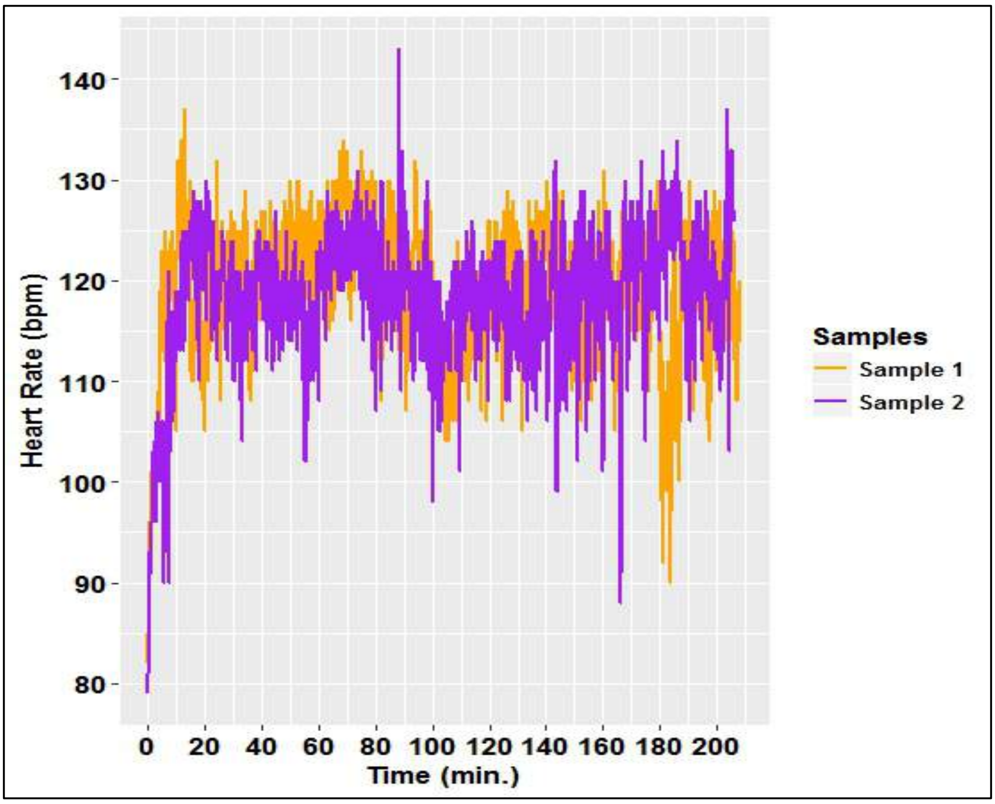


Figure 6: High Heart rate level for outdoor wall construction workers.

3.4. Non-climatic parameters

Sweat rate, skin temperature and core temperature are three important physiological heat stress indices and results from the current experiment are discussed below.

3.4.1. Skin temperature

In this study due to sudden rain and strong wind subjects, skin temperature and WBGT was decreased about 2 and 3°C respectively within 30 minutes. With a range of 36.5-27.4°C WBGT and 0.4ms^{-1} average wind velocity, skin temperature varied between 37.25-33.9 °C during the sampling period. Skin temperature fluctuation was uneven for all samples. Skin temperature increasing and decreasing depends on the ambient temperature, location, sweating rate and air velocity. In this study, 80% subjects skin temperature was above 35°C during work, which is above comfort level. In a hot environment, skin temperature is high due to sweat (Parsons, 2003). Outdoor wall construction workers (two workers) average skin temperature was 36.59 and 37.25 in 38% relative humidity, 34.1°C WBGT and 39.92 °C air temperature (average value of each parameter). In addition, mean skin temperature was 33.94°C when WBGT and relative humidity was 28.39°C, 65% respectively for the sample who assisted wall construction.

In different thermal condition, skin temperature responds much faster than core temperature. In different thermal condition, skin temperature responds much faster than core temperature. The comfort range of skin temperature is about 34-35°C (Epstein and Moran, 2006). From body to environment heat balance occurs through radiation and convection process, if the ratio between required heat evaporation (E_{req}) and maximum heat evaporation (E_{max}) exceed 0.2 workers start to feel discomfort and the range between 0.4-0.6 workers work performance will be decreased. Working time will be shorter when the heat evaporation value is above 0.6 and when it reaches to above 0.8 worker have a very good chance to health injury due to heat (Epstein and Moran, 2006).

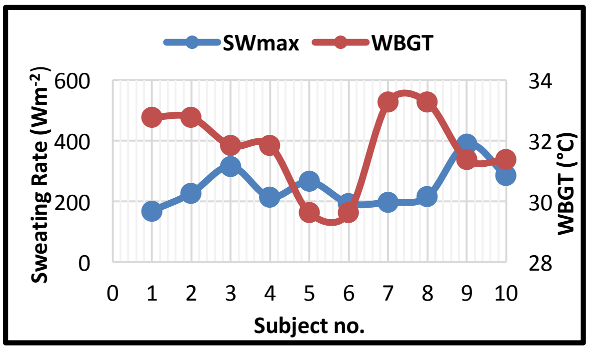
3.4.2. Core temperature

Physical work produces heat inside the body. The core temperature was calculated by heat balance equation (Equation 6) and also collected by using the device during the study period. Core temperature was found between 36.9-39.5°C in different temperature before worker start their work more precisely when their metabolic rate was 58 Wm-^{2}. The experimented value of core temperature was in the range of 36.2-37.6°C. After worker finished their work the core temperature was 36.9-40.5°C and 35.3-37.5°C in both calculated and experimental results respectively. Previous studies reported that 39°C account as a risk level for body core temperature and if it reaches to around 40°C it may cause life loss. The regular body core temperature is about 37°C (Lemke and Kjellstrom, 2012). If core temperature of subjects reaches 38.5-39°C different physical symptom is become exposed (Zhao, Zhu and Lu, 2009). In a high humid environmental condition sweat evaporation from the body is not enough though worker sweat frequently (Kjellstrom, 2016), but at a high air temperature, evaporation is the only way to heat reduction, which increases the level of core temperature (Kjellstrom *et al.*, 2016).

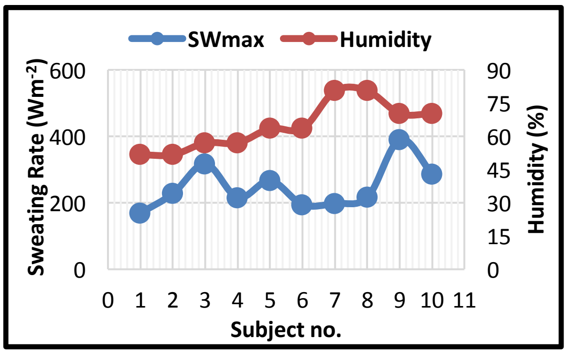
3.4.3. Sweating rate

Sweating helps to reduce the body temperature which increases with the workload. High workload, humid outside weather less sweating rate interrupt to reduce core temperature. The sweating rate increased when WBGT (Figure 7a) and humidity (Figure 7b) was less, where the sweating rate was decreased due to high WBGT and humidity (Figure 6). WBGT itself also consider the humid condition of nature. In this study four samples, SW_{max} was about 400 Wm^{-2}. According to, ISO 7933 the limit value of sweat rate 400 Wm^{-2} though not as extreme value but less than limit value will better for individuals (Brake and Bates, 2002). Excessive sweating rate cause of body water loss. Heat evaporation is important to balancing body temperature but the evaporative heat in a hot environment is not sufficient to remove the temperature of inside the body (Cena & Clark, 1981).

The previous study found that the sweating rate of the acclimatized sample is higher than the beginner (Malchaire *et al.,* 2000). Work in a hot environment required more water, every subject was needed to drink water several times. Drink frequent water helps to prevent dehydration. Dehydration has impacts on human comfort, health and also performance, due to excessive dehydration Kidney disease may occur (Kjellstrom *et al.,* 2009). For average people, 7.5% of body mass equal water loss is less dangerous than if core temperature is reached to above 40°C. 3% of body mass water loss is the limit of industrial worker and it increase worker heart rate (Parsons, 2003) and whereas ISO 7933 reported that 5% body mass water loss may keep safe about 95% of the worker.



7a



7b

Figure 7: Maximum sweating rate relation to WBGT (7a) and humidity (7b).

3.5. Cooling types

Two cooling methods (natural and artificial) were experimented at the end of the work to observe any differences in workers' heart rate and skin temperature during the resting period of 15 minutes. Table 2 shows, the heart rate and skin temperature before and after rest in both cooling condition. Natural wind speed was varied between 0.1-1.2ms^{-1} and workers heart rate decreased from 57bpm to 22bpm after the resting period. Figure 8 represents heart rate decreasing level of 10 workers with two different types of cooling methods used during the resting period. Under artificial wind, fan (air velocity 2ms^{-1}) plus natural wind (0.1-1.4ms^{-1}) workers heart rate were reduced from 50bpm to 15bpm. The decreasing heart rate was

Table 2: Heart rate (HR) and skin temperature (SK) in two different conditions (natural and artificial cooling condition)

Sample no.	Resting Conditions	HR Before rest	HR After rest	SK Before rest	SK After rest
1	Natural ventilation	88.34±20.40	87.23±12.42	36.66±0.61	35.79±0.256
2		105.41±14.84	115.58±6.82	35.81±1.07	35.2±0.35
3		110.28±10.92	92.56±6.73	34.52±1.41	35.42±0.01
4		99.64±8.56	92.52±4.87	35.78±0.42	35.97±0.14
5		97.72±8.62	81.30±7.25	34.51±0.98	32.4±0.11
6		88.64±8.84	65.48±6.04	35.32±1.21	33.7±0.16
7		89.12±7.76	76.86±3.63	35.65±1.43	31.23±0.48
8		97.27±9.41	81.23±3.90	35.28±0.74	32.94±0.21
9		119.81±5.76	100.70±4.56	35.23±0.39	34.88±0.10
10		118.69±7.02	99.42±5.48	35.32±0.68	36.14±0.14
1	Artificial air flow (Fan)	76.70±8.93	59.07±6.01	35.67±0.32	35.4±0.33
2		82.17±7.85	72.05±10.56	35.60±0.30	35.78±0.08
3		110.90±13.89	89.34±5.18	35.26±0.56	35.25±.15
4		99.46±9.27	85.55±5.13	33.93±0.88	33.88±0.40
5		93.47±7.83	73.23±7.13	34.97±0.97	33.74±0.37
6		89.54±8.26	77.69±12.98	34.86±0.48	34.88±0.28
7		87.67±8.70	71.55±4.29	34.98±1.72	32.63±0.34
8		87.12±4.6	72.40±5.54	34.84±0.96	33.57±0.23
9		120.31±14.10		36.59±0.36	36.24±0.13
10		119.79±7.66	96.09±12.12	37.26±0.48	35.6±0.71

influenced by some factors such as work intensity, skin temperature and core temperature relation. Low heart rate indicates low work intensity, if the maximum heart rate of a worker after work is low then the recovery level will also be lower. High airspeed makes skin temperature lower and because of that the core temperature increase (Huizenga *et al.*, 2004) which impair to reduce the heart rate (Jensen and Brabrand, 2015). In this study due to the short resting period, the core temperature was almost static only a few cases it increased 0.1-0.2°C.

Heart rate decreased at the beginning of the resting period in both cooling systems. Under artificial cooling, heart rate reduced after 2-4 minutes of resting period and remained constant for rest of the time. However, in natural wind, heart rate decreased similarly as artificial wind, although the rate fluctuated afterward.

Skin temperature reduced about 0.4°C in natural ventilation system with different environmental conditions (e.g. high WBGT (32.5°C) and moderate WBGT (28°C) with low air velocity 0.1 ms-1 and high-velocity 0.8ms-1). On the other hand, workers skin temperature reduced 0.9°C under artificial cooling by a fan. Reduction of skin temperature fluctuated in natural ventilation while temperature reduced gradually in the artificial ventilation system.

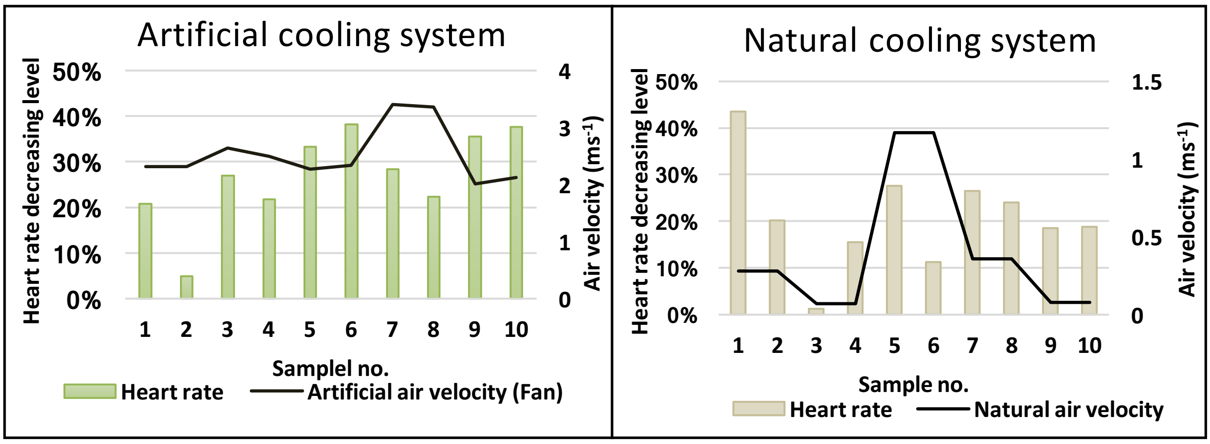


Figure 8: Two different cooling system and heart rate decreasing rate

4. Conclusion

Current research suggests (based on acclimatized subjects physical responses) that if a worker works in two shifts (early morning and afternoon) and stop working (around 5-6 hours) during mid-period of the summer day, they can reduce the risks of health injury and frequencies of a break. However further investigation is necessary on a worker who works in direct sun exposure. Nevertheless, our findings will help to understand labor physiological responses under hot working conditions and make people concern about shifting working schedule.

5. Acknowledgement

The authors would like to express their special gratitude to all the subjects in the experiment.

6. References

ASHARE HANDBOOK, 2009. *Fundamentals*. W. Stephen Comstock.

Bröde, P., Fiala, D., Lemke, B., & Kjellstrom, T. (2017). Estimated work ability in warm outdoor environments depends on the chosen heat stress assessment metric. *International Journal of Biometeorology*, 1–15. https://doi.org/10.1007/s00484-017-1346-9.

Brake, D. J. and Bates, G. P. (2002). Limiting metabolic rate (Thermal Work Limit) as an index of thermal stress. *Applied Occupational and Environmental Hygiene*, 17(3), pp. 176–186. doi: 10.1080/104732202753438261.

Cheung, S. S., Lee, J. K. W., & Oksa, J. (2016). *Employment Standards 1*, 164(June), 148–164.

Cena, K. & Clark, J. A. (1981). Bioengineering, Thermal Physiology and Comfort. *British journal of industrial medicine*. doi: 10.1136/oem.38.3.308.

Dunne, J. P., Stouffer, R. J., & John, J. G. (2013). Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*, 3(6), 563–566. https://doi.org/10.1038/nclimate1827.

Epstein, Y. and Moran, D. S. (2006). Thermal Comfort and the Heat Stress Indices. *Industrial Health*, 44(3), pp. 388–398. doi: 10.2486/indhealth.44.388.

Fox, K. *et al.* (2007). Resting Heart Rate in Cardiovascular Disease. *Journal of the American College of Cardiology*, 50(9), pp. 823–830. doi: 10.1016/j.jacc.2007.04.079.

Hijioka, Y., E. Lin, J.J. Pereira, R.T. Corlett, X. Cui, G.E. Insarov, R.D. Lasco, E. Lindgren, & A. S. (2014). *Asia. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* https://doi.org/10.1017/CBO9781107415386.004.

Hondula, D. M., Rocklöv, J., & Sankoh, O. A. (2012). Past, present, and future climate at select indepth member health and demographic surveillance systems in Africa and Asia. *Global Health Action*, 5(SUPPL.), 74–86. https://doi.org/10.3402/gha.v5i0.19083.

Huizenga, C., Zhang, C., Arens, E. & Wang, E. (2004). Skin and core temperature response to partial- and whole-body heating and cooling. *Journal of Thermal Biology*, 29(7–8 SPEC. ISS.), pp. 549–558. doi:

10.1016/j.jtherbio.2004.08.024.
ISO/DIS 7243 (2015) *Ergonomics of the thermal environment—assessment of heat stress using the WBGT (wet bulb globe temperature)* index (ISO/DIS 7243:2015).
INABA, R., KUROKAWA, J. and MIRBOD, S. M. (2009). Comparison of Subjective Symptoms and Cold Prevention Measures in Winter between Traffic Control Workers and Construction Workers in Japan. *Industrial Health*, 47(3), pp. 283–291. doi: 10.2486/indhealth.47.283.
Jensen, M. M. & Brabrand, M. (2015). The relationship between body temperature, heart rate and respiratory rate in acute patients at admission to a medical care unit. *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine*, 23(Suppl 1), p. A12. doi: 10.1186/1757-7241-23-S1-A12.
Kjellstrom, T. (2016). Impact of Climate Conditions on Occupational Health and Related Economic Losses. *Asia Pacific Journal of Public Health*, 28(2_suppl), 28S–37S. https://doi.org/10.1177/1010539514568711.
Kjellstrom, T., Briggs, D., Freyberg, C., Lemke, B., Otto, M., & Hyatt, O. (2016). Heat, Human Performance, and Occupational Health: A Key Issue for the Assessment of Global Climate Change Impacts. *Annual Review of Public Health*, 37(1), 97–112. https://doi.org/10.1146/annurev-publhealth-032315-021740.
Kjellstrom, T., Holmer, I., & Lemke, B. (2009). Workplace heat stress, health and productivity-an increasing challenge for low and middle-income countries during climate change. *Global Health Action*, 2(1), 1–6. https://doi.org/10.3402/gha.v2i0.2047.
Li, X.,Chow, K., Zhu, Y. & Lin, Y. (2016). Evaluating the impacts of high-temperature outdoor working environments on construction labor productivity in China: A case study of rebar workers'. *Building and Environment*. Elsevier Ltd, 95, pp. 42–52. doi: 10.1016/j.buildenv.2015.09.005
Lemke, B. & Kjellstrom, T. (2012). Calculating Workplace WBGT from Meteorological Data: A Tool for Climate Change Assessment. *Industrial Health*, 50(4), pp. 267–278. doi: 10.2486/indhealth.MS1352.
Mairiaux, P. and Malchaire, J. (2015). Workers self-pacing in hot conditions: A case study. *Applied Ergonomics*, 6870(July 1985). doi: 10.1016/0003-6870(85)90209-1.
Malchaire, J., Kampmann, B., Havenith, G., Mehnert, P., & Gebhardt, H. J. (2000). Criteria for estimating acceptable exposure times in hot working environments: A review. *International Archives of Occupational and Environmental Health,* 73(4), 215–20. https://doi.org/10.1007/s004200050420.
Périard, J. D., Racinais, S. & Sawka, M. N. (2015). Adaptations and mechanisms of human heat acclimation: Applications for competitive athletes and sports. *Scandinavian Journal of Medicine and Science in Sports*, 25(S1), pp. 20–38. doi: 10.1111/sms.12408.
Pittaras, A. M., Faselis, C., Doumas, M., Myers, J., Kheirbek, R., Kokkinos, J. P., Tsimploulis, A., Aiken, M., & Kokkinos, P. (2013). Heart rate at rest, exercise capacity, and mortality risk in veterans. *American Journal of Cardiology*. Elsevier Inc, 112(10), pp. 1605–1609. doi: 10.1016/j.amjcard.2013.07.042.
Parsons, K. (2003) *Human thermal environments*, *Chemistry & …*. doi: 10.1201/b16750.
Ramsey, J. D. (1995). Task performance in heat: A review. *Ergonomics*, 38(1), 154–165. https://doi.org/10.1080/00140139508925092.
World Health Organization (1969). *Technical Report series 412*, *Health factors involved in working under conditions of heat stress*. Available at: http://whqlibdoc.who.int/trs/WHO_TRS_412.pdf.
XIANG, J., BI, P., PISANIELLO, D., and HANSEN, A. (2014). Health Impacts of Workplace Heat Exposure: An Epidemiological Review. *Industrial Health*, 52(2), pp. 91–101. doi: 10.2486/indhealth.2012-0145.
Zhao, J., Zhu, N. & Lu, S. (2009). Productivity model in hot and humid environment based on heat tolerance time analysis. *Building and Environment*. Elsevier Ltd, 44(11), pp. 2202–2207. doi: 10.1016/j.buildenv.2009.01.003.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Can regular exposure to elevated indoor temperature positively affect metabolism in overweight elderly men?

Hannah Pallubinsky[1], Bas Dautzenberg[1], Esther Phielix[1], Marleen A. van Baak[1], Patrick Schrauwen[1] and Wouter D. van Marken Lichtenbelt[1]

[1] Maastricht University, NL, Department of Human Biology and Human Movement Sciences, h.pallubinsky@maastrichtuniversity.nl

Abstract: Thermoneutrality of indoor environments is suspected to be involved in the current 'diabesity epidemic'. Regular exposure to elevated temperature might have positive implications for metabolic and cardiovascular health. This study investigated the effect of prolonged exposure to elevated ambient temperature (passive mild heat acclimation, PMHA) on fasting plasma glucose (FPG) and insulin (FPI) values, thermophysiology and thermal perception in an overweight population. 11 overweight elderly men (65.7±4.9y, BMI 30.4±3.2kg/m^2, HOMA-IR 4.3±2.4) underwent PMHA (10d, 34.4±0.2˚C, 4-6h/d). Pre- and post-PMHA, FPG and FPI samples were taken. A temperature-ramp-protocol was conducted to assess adaptation of thermophysiological parameters pre-/post-PMHA. Thermal sensation (TS) and thermal comfort (TC) were evaluated during PMHA, at 1-hour intervals. FPG, FPI, HOMA-IR and Tcore decreased significantly after PMHA (ΔFPG:-0.27mmol/L, P=.036; ΔFPI:-12.69pmol/L, P=.026; ΔHOMA-IR:-0.7, P=.012; ΔTcore:-0.17±0.19˚C, P=0.017). Insulin sensitivity, Tskin and sweating did not change. MAP decreased (Δ-2.91±2.67 mmHg, P=0.007); heart rate tended to decrease (Δ-2.98±3.50bpm, P=0.065) post PMHA. TS increased while TC decreased during the day, but both remained unchanged post-PMHA. This study is the first to show that PMHA induces significant thermophysiological and cardiovascular changes and may affect glucose metabolism in overweight elderly men.

Keywords: Indoor temperature, passive mild heat acclimation, glucose metabolism, metabolic health, thermal comfort

1. Introduction

In the Western World, we are currently facing a very high prevalence of overweight, obesity, obesity-induced insulin resistance and Type 2 Diabetes: since 1980, obesity has more than doubled worldwide and the number of people suffering from diabetes has risen from 108 million to 422 million in 2014 (Mathers et al., 2006, Who, 2016). Overweight and obesity are major risk factors for the development of Type 2 Diabetes. Current therapy standards fail to effectively tackle the problem: although exercise therapy, healthy diet or a combination of both have been shown to be very effective in preventing and treating metabolic diseases, therapy adherence is often low and long-term weight reduction and improved insulin sensitivity are rarely accomplished (Stunkard et al., 1979, Garner et al., 1991). Therefore, it is of great importance to explore new horizons to prevent and treat obesity and metabolic diseases effectively, and to keep the rapidly increasing numbers of new cases at bay.

Recently, it has been suggested that regular exposure to warmth might have positive implications for metabolic and cardiovascular health (Mcallister et al., 2009, Moellering et al., 2012). Regular bathing in hot water has been shown to significantly improve cardiovascular function in young, healthy volunteers (Brunt et al., 2016a, Brunt et al., 2016b). In a study by Hooper (Hooper, 1999), it was shown that glucose handling improved significantly in T2DM patients after daily hot baths over the course of 3 weeks. Interestingly, seasonal variations of HbA1c (glycosylated haemoglobin, an indicator for severity of insulin resistance) have also previously been described in the literature in both healthy adults (Macdonald et al., 1987) and T2DM patients (Asplund, 1997, Gikas et al., 2009, Iwata et al., 2012), indicating that HbA1c is lower during the summer months and therefore suggests improved glycaemic control during warmer times of the year.

In an animal model, it has furthermore been shown that heat treatment, both acute and on the longer term, improved insulin sensitivity in rodent skeletal muscle (Kokura et al., 2007, Gupte et al., 2009, Sareh et al., 2011, Gupte et al., 2011). In an earlier study, we have shown that passive and relatively mild heat acclimation (PMHA, ~33˚C ambient temperature for 6h a day, at 7 consecutive days), representing realistic Western and central European conditions during a warm summer or a heat wave, induces thermophysiological changes in young healthy men (Pallubinsky et al., 2017). A significant decrease of core temperature as well as reduced blood pressure was evident after PMHA in the earlier study, which has also frequently been reported in many other, more intense heat acclimation studies (for example (Nadel et al., 1974, Nielsen et al., 1993, Buono et al., 1998, Pandolf, 1998, Taylor, 2014)).

We hypothesise that PMHA beneficially affects glucose metabolism and cardiovascular health in humans. Moreover, we hypothesise that PMHA affects thermal comfort and thermal sensation resulting in improved satisfaction with the thermal environment.

Therefore, this study evaluated the effect of PMHA on glucose metabolism (fasting plasma glucose (FPG) and fasting plasma insulin (FPI)), cardiovascular and thermophysiological parameters as well as thermal comfort and thermal sensation in an overweight elderly population.

2. Methods

In total, 11 elderly overweight Caucasian men volunteered in the study (Table 1). Participants gave their written informed consent. During screening, all were checked for their medical history. Exclusion criteria included uncontrolled hypertension, active cardiovascular disease, liver or kidney dysfunction, smoking and use of beta-blockers or other medication known to interfere with glucose metabolism. Fasting glucose and 2-h glucose during an oral glucose tolerance test (OGTT) were also determined during the screening. Participants with (previously undiagnosed) T2DM were excluded from the study based on the OGTT (2-h glucose > 11.1mmol/L). All participants were instructed to use their medication as usual during the study to avoid potential disturbances caused by irregularities.

Participants had not undertaken any sort of formal acclimation and had not spent time in a hot environment at least 2 months previous to their participation. To avoid an effect of circadian rhythm on the outcome parameters, all testing and acclimation days commenced at the same time in the morning.

Table 1. Participant characteristics, N=11

	Mean±SD
Age [years]	**65.7±4.9**
BMI [kg/m2]	**30.4±3.2**
Fat percentage [%]	**28.5±4.6**
Fasting glucose [mmol/L]	**6.0±0.5**
2-h Glucose [mmol/L]	**7.6±1.9**

Participants were exposed to 10 days of passive mild heat acclimation (PMHA) (Figure 1). Before and after PMHA, blood samples were taken to indicate FPG and FPI and to calculate HOMA-IR (a method do estimate insulin resistance). Moreover, a temperature ramp protocol was performed to study physiological and cardiovascular response to increasing ambient temperatures. The increasing temperature ramp before and after PMHA will be referred to as UP in the following (Figure 1 and 2). During PMHA, thermal comfort (7-point visual analogue scale) and thermal sensation (ASHRAE-scale) were assessed every hour.

Before measurement day 1, 2, 11 and 12 (Figure 1), participants consumed self-chosen standardized evening meals, with a comparable composition of nutrients. At day 1 and 12, participants arrived in the morning after an overnight fast (as of 22:00h the previous evening) and blood samples were taken via an intravenous catheter. Blood plasma samples were centrifuged, plasma was snap-frozen in liquid nitrogen and stored at -80˚C for later analysis for glucose, insulin and free fatty acid concentrations.

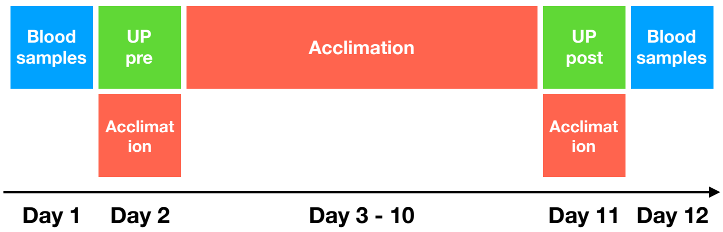


Figure 1. Protocol time line

2.1. UP protocol

For protocol UP, participants arrived at the laboratory in the morning after an overnight fast (as of 22:00h the previous evening). Upon arrival, participants ingested a telemetric pill (Vital Sense, Philips Healthcare, NL) to measure core temperature, which was monitored using an Equivital apparatus mounted to the participant with a chest strap (Equivital Hidalgo, UK). Heart rate was measured with the same Equivital device. Core temperature, heart rate and skin temperatures were recorded at 1-min intervals. To measure mean skin temperature, wireless skin temperature sensors (iButtons, Maxim Integrated Products, California, USA) were attached to 14 ISO-defined body sites (Iso, 2004) with semi-adhesive tape (Fixomull stretch, BDN medical GmbH, GER).

In a climate chamber, participants took place on a stretcher with air-permeable fabric. Upper arm blood pressure was recorded using the oscillometric principle (Omron M6 Comfort IT, Omron Healthcare, JPN). Immediately before entering the climate chamber and after leaving it, participants were weighed (after towelling themselves thoroughly after UP) to determine total water loss, which was calculated by the difference in total body mass before and after the UP protocol.

When preparations were finished, UP started with a baseline period of 60 min followed by an increase of the ambient temperature over the course of 120 min (Figure 2). The baseline temperature (28.8±0.15˚C) was assumed to be neutral for a resting semi-nude person, based on the literature review of Kingma *et al.* (Kingma et al., 2012) and it was corrected for the isolation of the stretcher that participants rested on during the testing. Relative humidity was allowed to drift freely with the changes in temperature, resulting in an average relative humidity of 23.2±3.3% during the test.

The first 30 min of protocol UP were regarded as familiarisation period, and therefore excluded from the data analysis. For the comparisons of physiological variables during UP, three periods were selected: baseline, T1, T2 and T3 (Figure 2). Blood pressure was only measured at baseline, T2 and T3.

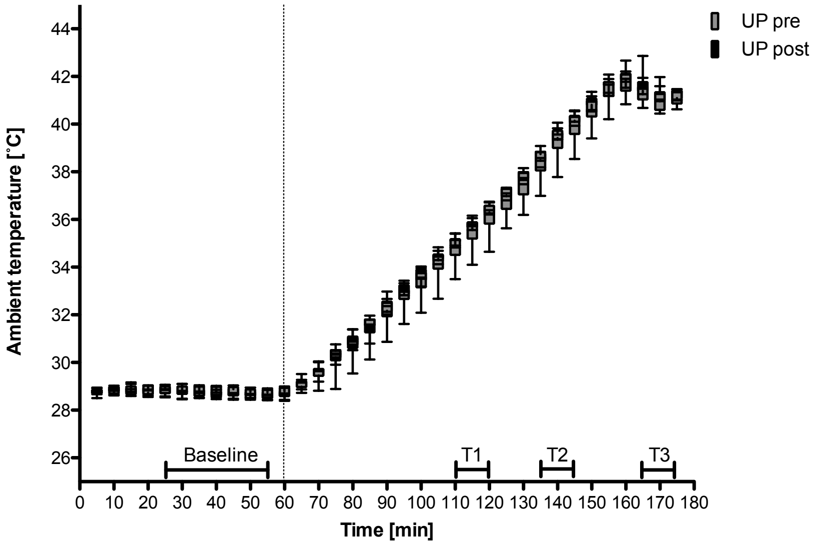


Figure 2. Experimental conditions during UP before and after acclimation. Four time-intervals were selected to compare data before and after PMHA (protocol time and ambient temperature in brackets): baseline (min 25-55: 28.8±0.15˚C), T1 (min 110-120: 35.4±0.40˚C), T2 (min 135-145: 38.9±0.49˚C) and T3 (min 165-175: 41.3±0.33˚C), N=11.

2.2. Passive mild heat acclimation

PMHA started in the afternoon of study day two (Figure 1). During the first and last sequence of PMHA (day 2 and 11), participants stayed in a 'warm chamber' for 4 hours. During the remaining 8 days of PMHA, participants acclimatised for 6 hours per day. From earlier heat acclimation studies (for example (Moseley, 1997, Pandolf, 1998)), we know that the most important changes with respect to thermophysiology are expected to occur within the first 2-7 days of repeated heat exposure. Therefore, we applied a 10-day acclimation protocol, expecting a sufficiently long acclimation period to induce the anticipated adaptive reactions (Pandolf, 1998). Ambient temperature in the warm chamber was kept constant at 34.4±0.2˚C; and relative humidity was 22.8±2.7%, which classifies the ambient air as dry. All participants successfully completed PMHA.

During their stay in the acclimation chamber, participants remained seated at a desk and were allowed to perform regular office work (1.2METs). Participants wore standardised clothing composed of underwear, T-shirt, shorts and socks/slippers. The total thermal resistance of the clothing ensemble plus the desk chair added up to approximately 0.41clo (Mccullough et al., 1989, Mccullough et al., 1994). Participants had unlimited access to water; and food was provided upon request, in order to not influence habitual diet. They were allowed to leave the chamber for toilet breaks.

2.3. Data analyses

The software packages Microsoft Office 2011 Excel (Microsoft) and SPSS 23 for Mac (SPSS Inc.) was used for data analyses. Mean±SD, delta values and relative changes were calculated for all parameters. Paired-sample t-tests were used to compare the measured parameters before and after PMHA. As the blood sampling failed for one participant, blood parameters are presented as N=10. Statistical significance was considered for P≤0.05 and a statistical trend was considered if 0.05<P<0.10. Data is presented as mean±SD.

3. Results

3.1. Blood plasma concentrations

Fasting plasma glucose (FPG, P=0.013) and fasting plasma insulin (FPI, P=0.026) were significantly lower post PMHA (Table 2). HOMA-IR as determined by FPG and FPI decreased significantly post PMHA (pre 4.3±2.4, post 3.6±2.1, Δ0.71, P=0.011). Before PMHA, 2 participants (no. 3 and 9) exhibited a HOMA-IR <2.9, which indicates early insulin resistance, the remaining 8 participants were classified as significantly insulin-resistant (HOMA-IR >2.9). After PMHA, 2 of 10 participants were classified as early insulin resistant (no. 3 and 5) and 1 as insulin-sensitive (no. 9, HOMA <1.0), whereas the remaining participants were still classified as being insulin-resistant (HOMA-IR >2.9).

Table 2. Fasting plasma glucose, fasting plasma insulin and free-fatty acid levels before and after PMHA

	Pre PMHA	**Post PMHA**	**Δ**	**P-value**
Fasting plasma glucose [mmol/L]	**6.0±0.50**	**5.8±0.4**	**-0.2±0.4**	**0.013***
Fasting plasma insulin [pmol/L]	**96.7±54.7**	**84.0±49.3**	**-12.7±15.1**	**0.026***

Data is presented as mean±SD. N=10. Δ denotes changes post vs. pre PMHA, * indicates P<.05 for changes post PMHA.

3.2. Thermophysiological and cardiovascular responses

After PMHA, Tcore was significantly decreased by -0.13±0.18°C at baseline (P=0.035), T1 (-0.19±0.26, P=0.036) and T2 (-0.18±0.25˚C, P=0.041) and tended towards a decrease at T3 (-0.10±0.52˚C, P=0.073) during the UP protocol, compared with Tcore values before PMHA (Table 4). Mean skin temperature remained unchanged by PMHA. Total sweat loss as measured by the change in weight before and after UP did not change with PMHA (Δpre 0.253±0.066kg, Δpost 0.237±0.049kg, P=0.175)

Post-PMHA, MAP significantly decreased at baseline and T2 compared with MAP values before PMHA, but at T3 the decrease was no longer significant (MAP baseline: pre 93±8, post 90±8, Δ-3±4, P=0.020; T2: pre 93±9, post 90±10, Δ-4±3, P=0.002, T3: pre 92±7, post 90±8, Δ-2±5, P=0.147). Heart rate was unchanged at baseline but decreased at T1 and T3 and showed a trend towards decrease at T3 compared with heart rate values before PMHA (HR baseline: pre 64±11, post 63±9, Δ-2±4, P=0.185; T1: pre 70±8, post 67±8, -3±3, P=0.040; T2: 71±11, post 67±11, Δ-4±4, P=0.010; T3: pre 73±11, post 70±10, Δ3±4, P=0.010).

3.3. Thermal sensation and thermal comfort during PMHA

TC decreased while TS increased during the day, but both remained unchanged at day 9 when compared with day 2 of PMHA (Figure 3).

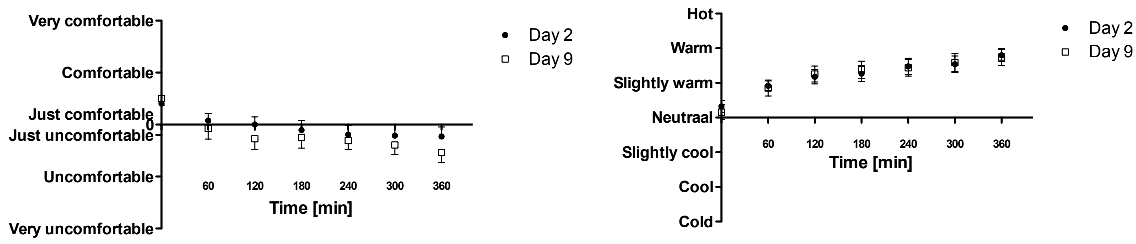


Figure 3. Thermal comfort and thermal sensation during day 2 and day 9 of PMHA. Error bars represent ±SEM, n=11.

4. Discussion and conclusion

The present study investigated the effect of passive mild heat acclimation (PMHA) on glucose metabolism, thermophysiological and cardiovascular factors as well as thermal comfort and thermal sensation in overweight elderly men. We show for the first time that the relatively mild, passively administered heat acclimation evoked substantial changes of glucose metabolism: fasting plasma glucose (FPG), and fasting plasma insulin (FPI) decreased significantly after PMHA. We confirmed our earlier findings on the thermophysiological effects of PMHA, showing that the applied acclimation model evoked significant changes of core temperature (Tcore), which is an important indicator for successful acclimation. Moreover, mean arterial pressure (MAP) and heart rate were significantly reduced, suggesting that passive exposure to elevated temperature brings along beneficial effect for cardiovascular health and induces greater resilience to heat.

4.1. Glucose metabolism

FPG and FPI significantly decreased upon PMHA. HOMA-IR, which is calculated based on fasting plasma glucose and fasting plasma insulin values, also improved on average by approximately 17%. It has earlier been suggested that in physiological studies, HOMA-IR can be used to indicate basal function “at the nadir of the dose-response curve, whereas clamps are an assessment of the stimulated extreme…” (Wallace et al., 2004). The decreased HOMA-IR post PMHA might be an indication for an improved balance between hepatic glucose output and insulin secretion in a basal state (Wallace et al., 2004). Based on the latter, it might be cautiously suggested that PMHA improved hepatic insulin sensitivity but not peripheral insulin sensitivity, but additional measurements and analyses are required to verify this hypothesis.

4.2. Thermophysiological and cardiovascular responses

PMHA elicited significant thermophysiological adaptations in the present study, causing a decrease of Tcore during thermoneutral conditions and during warming. Moreover, a distinct decrease of mean arterial pressure (MAP) was evident as well as a lowering of heart rate during warming.

In an earlier study, we have shown that in a young healthy population, a 7-day PMHA protocol elicited significant thermophysiological and cardiovascular changes which were similar to those typically reported after more intense, often exercise-induced heat acclimation studies (Pallubinsky et al., 2017). The present investigation confirms the effectiveness of PMHA also in an overweight elderly population. An average overall decrease of Tcore of approximately -0.17˚C in the present study is even more pronounced than in the earlier PMHA study in healthy participants, where Tcore decreased by approximately -0.14˚C post PMHA, which might, amongst other things, be due to the longer duration of acclimation (10 days vs. 7 days) and the slightly higher acclimation temperature (~34.5˚C vs. 33˚C). Moreover, in both studies, we observed a significant decrease of blood pressure. Especially in the present study, the observed reduced mean arterial pressure (MAP) and reduced heart rate during warming is a highly favourable result as hypertension represents a frequent medical issue in overweight and elderly individuals. Note that in the present study, four out of eleven participants were previously diagnosed with high blood pressure and three of those were using antihypertensive drugs during the study. Prolonged and more frequent exposure to warm thermal environments might help to alleviate hypertension and potentially even facilitate a reduced need for medication.

4.3. Thermal comfort and thermal sensation

Thermal comfort and thermal sensation did not improve after PMHA. Importantly, at no point in time, participants voted to feel either 'very uncomfortable' or 'very hot' during PMHA. On average, thermal comfort ranged between 'just comfortable' and 'just uncomfortable' to 'uncomfortable' during the day. Thermal sensation increased from 'neutral' to 'warm' over the course of the 6h of PMHA during both day 2 and day 9. Although an improvement of thermal comfort and a decrease of thermal sensation was anticipated previous to the study, no significant change occurred post-PMHA. Interestingly, thermal comfort even decreased a little bit at day 9 of PMHA at most time-points, but this decrease was not significant when compared with the voting of day 2.

4.4. Limitations and future perspectives

This study provides information on the effect of PMHA on glucose metabolism, thermophysiological and cardiovascular parameters. However, with respect to the general interpretation of the study results, a few limitations need to be taken into consideration.

Firstly, the study population was limited to a group of overweight elderly men, and therefore, more information on the effect of PMHA on metabolic, thermophysiological and cardiovascular parameters in other populations, and especially in women, is needed. Secondly, although participants were asked to not deviate from their normal lifestyle and habitual physical activity, we did not record any information with respect to diet and exercise during the study period. Therefore, future studies should include measurements of dietary intake and physical activity.

4.5. Conclusions

This study shows that passive acclimation to mildly elevated temperatures significantly lowers FPG, FPI and HOMA-IR in an overweight elderly population. Tcore was lowered by PMHA, both in a thermoneutral condition and during warming. Moreover, MAP was lowered in thermoneutrality and during warming, as well as heart rate, which was also decreased during warming post-PMHA. This indicates beneficial health effects of heat acclimation for the specific study group, as cardiovascular diseases are commonly encountered in overweight and elderly people. Thermal comfort and thermal sensation did not improve after PMHA, but remained within reasonable limits during PMHA.

More research is needed to further investigate the mechanisms which cause warmth to affect glucose metabolism. A better understanding of the underlying relationship between warmth exposure and glucose metabolism can help with the design of healthier indoor environments, alongside with the development of tailor-made anti-obesity and insulin-sensitizing temperature interventions.

5. References

Asplund, J. 1997. Seasonal variation of HbA1c in adult diabetic patients. *Diabetes care,* 20, 234.

Brunt, V. E., et al. 2016a. Passive heat therapy improves cutaneous microvascular function in sedentary humans via improved nitric oxide-dependent dilation. *J Appl Physiol (1985),* 121, 716-23.

Brunt, V. E., et al. 2016b. Passive heat therapy improves endothelial function, arterial stiffness and blood pressure in sedentary humans. *J Physiol,* 594, 5329-42.

Buono, M. J., et al. 1998. Acclimation to humid heat lowers resting core temperature. *Am J Physiol,* 274, 1295-9.

Garner, D. M., et al. 1991. Confronting the Failure of Behavioral and Dietary Treatments for Obesity. *Clinical Psychology Review,* 11, 729-780.

Gikas, A., et al. 2009. Seasonal variation in fasting glucose and HbA1c in patients with type 2 diabetes. *Prim Care Diabetes,* 3, 111-4.

Gupte, A. A., et al. 2009. Heat treatment improves glucose tolerance and prevents skeletal muscle insulin resistance in rats fed a high-fat diet. *Diabetes,* 58, 567-78.

Gupte, A. A., et al. 2011. Acute heat treatment improves insulin-stimulated glucose uptake in aged skeletal muscle. *J Appl Physiol (1985),* 110, 451-7.

Hooper, P. L. 1999. Hot-tub therapy for type 2 diabetes mellitus. *N Engl J Med,* 341, 924-5.

ISO 2004. Ergonomics - Evaluation of thermal strain by physiological measurements. *ISO 9886:2004.* Geneva: International Standards Organization.

Iwata, K., et al. 2012. Seasonal variation in visceral fat and blood HbA1c in people with type 2 diabetes. *Diabetes Res Clin Pract,* 96, 53-4.

Kingma, B. R. M., et al. 2012. The thermoneutral zone: implications for metabolic studies. *Front Biosci (Elite Ed),* 4, 1975-85.

Kokura, S., et al. 2007. Whole body hyperthermia improves obesity-induced insulin resistance in diabetic mice. *Int J Hyperthermia,* 23, 259-65.

MacDonald, M. J., et al. 1987. Seasonality in glycosylated hemoglobin in normal subjects. Does seasonal incidence in insulin-dependent diabetes suggest specific etiology? *Diabetes,* 36, 265-8.

Mathers, C. D., et al. 2006. Projections of global mortality and burden of disease from 2002 to 2030. *Plos Medicine,* 3.

McAllister, E. J., et al. 2009. Ten putative contributors to the obesity epidemic. *Crit Rev Food Sci Nutr,* 49, 868-913.

McCullough, E. A., et al. 1989. A database for determining the evaporative resistance of clothing. *ASHRAE Trans,* 95.

McCullough, E. A., et al. 1994. Thermal insulation provided by chairs. *ASHRAE Trans,* 100.

Moellering, D. R., et al. 2012. Ambient Temperature and Obesity. *Curr Obes Rep,* 1, 26-34.

Moseley, P. L. 1997. Heat shock proteins and heat adaptation of the whole organism. *J Appl Physiol (1985),* 83, 1413-7.

Nadel, E. R., et al. 1974. Mechanisms of thermal acclimation to exercise and heat. *J Appl Physiol,* 37, 515-20.

Nielsen, B., et al. 1993. Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. *J Physiol,* 460, 467-85.

Pallubinsky, H., et al. 2017. Thermophysiological adaptations to passive mild heat acclimation. *Temperature (Austin),* 4, 176-186.

Pandolf, K. B. 1998. Time course of heat acclimation and its decay. *Int J Sports Med,* 19 Suppl 2, 157-60.

Sareh, H., et al. 2011. Response of mice to continuous 5-day passive hyperthermia resembles human heat acclimation. *Cell Stress Chaperones,* 16, 297-307.

Stunkard, A. J., et al. 1979. Behavior modification in the treatment of obesity. The problem of maintaining weight loss. *Arch Gen Psychiatry,* 36, 801-6.

Taylor, N. A. 2014. Human heat adaptation. *Compr Physiol,* 4, 325-65.

Wallace, T. M., et al. 2004. Use and abuse of HOMA modeling. *Diabetes care,* 27, 1487-1495.

WHO. 2016. *Obesity and overweight* [Online]. Available: http://www.who.int/mediacentre/factsheets/fs311/en/ [Accessed].

WORKSHOP 8

Personal Comfort Systems

Invited Chairs:
Sally Shahzad and Gail Brager

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Self-Learning Framework for Personalised Thermal Comfort Model

Yiqiang Zhao[1], Kate Carter[1], Fan Wang[2], Ola Uduku[3] and Dave Murray-Rust[4]

[1] Edinburgh School of Architecture and Landscape Architecture, Edinburgh College of Art, University of Edinburgh, Edinburgh, UK
[2] The Centre of Excellence in Sustainable Building Design, School of Energy, Geosciences, Infrastructure and Society, Heriot-Watt University, UK
[3] Manchester School of architecture, UK
[4] School of Design, Edinburgh College of Art, University of Edinburgh, Edinburgh, UK

Abstract: This paper presents a novel self-learning framework for building personalised thermal comfort model. The framework is built with the understanding that each occupant has a unique thermal comfort preference. Current thermal comfort models focus on analysing average data for groups of people in different types of building, rather than considering individual thermal preference. We argue that building a personal level comfort model using learning algorithms may provide the basis to represent personalised dynamic thermal demands. By bringing more personal interest and data, the ground-up personalised model may help us better understand the internal links of personal factors from psychology, physiology and behavioural aspects. Furthermore, we developed an Smart Thermal Comfort (STC) environment sensors and mobile application to efficiently collect distributed personal data and make it open-sourced for other researchers to use. The aim of this paper is to rethink current comfort studies to standardize the methods in modelling personalised thermal comfort. By summarising the past five years' papers on personal thermal comfort model, this paper critically evaluates the methods used for personal data collection and learning algorithms. Finally, we conclude an Personal Thermal Comfort (PTC) framework including distributed personal measurement tools and machine learning algorithm for personalised thermal comfort study.

Keywords: Personal thermal comfort, adaptive behaviour, machine learning, digital data collection tool.

1. Introduction

At present the definition of Predicted Mean Vote (PMV) is based on large population statistical laboratory studies (Fanger, 1970), as a standard in ASHRAE 55 and ISO7730, and is widely used in Building Energy Simulation (BES) programs all over the world. However, many studies show that the PMV model has been unsuccessful in representing occupants actual thermal sensation vote (Yang and Zhang, 2008; Daghigh et al., 2009; De Dear et al., 1998; Humphreys, 1978; Deuble and de Dear, 2014). The emerging adaptive thermal comfort model which considers occupants' behaviour as an important factor has therefore become a more popular method to meet the dual targets of occupant thermal comfort and energy efficiency (De Dear et al., 1998).

However, most of these studies focus on modelling based on average group data statistics and ignore the localised or personal thermal preference differences at individual levels (Jazizadeh et al., 2013; Jiang and Yao, 2016; Y. Zhao et al., 2014; Auffenberg et al., 2015). In other word, there is a gap between individual and group level thermal comfort requirements. At the same time, as the rapid development of the concept of "smart home", such as thermostats from Nest, Ecobee, Netatmo etc., the thermal demand from home or personal level also increase the importance of building comfort model for small groups of people or individuals. Based on this gap, recent papers proposed different individual thermal sensation models which are appropriate for different types of building (Auffenberg et al., 2015; Jiang and Yao, 2016; Gao and Keshav, 2013; Q Zhao et al., 2014; Liu et al., 2007; Jiang et al., 2017). In relation to the sample size or model applicability, fundamental studies are still needed to clearly examine how the individual personal thermal comfort model is produced and how to apply it into Building Energy Systems.

The outcome of this paper is the proposal of a self-learning framework for personalised thermal comfort model. Under this framework, this paper critically discusses current personalised comfort studies in three parts: the importance of personal thermal comfort model, next generation data collection tools and learning algorithms comparison. First, based on thermal regulation system, we critically evaluate the position of PMV and adaptive model. By suggesting treating personal model by narrow and broad sense, we analysed the importance of individual difference and its potential requirement for data collection tools. Second, the way occupants interacted with the built environment is challenged by different digital data collections tools, especially personal measurement. For example, mobile apps have the function of positioning, wireless data transitioning and easy-to-use user interface which could profoundly decrease data collection difficulty and increase data diversity. We listed several commonly used devices, compared them with some latest digital technology and summarised some new possibilities in personal comfort modelling. Third, by reviewing several latest personal comfort algorithm studies, we introduced three basic machine learning algorithms: Logistic Regression, Support Vector Machine and Artificial Neural Network.

2. Why personal thermal comfort model?

Currently, personal comfort models are commonly built to cooperate with Personal Condition System. In PCS, energy is only deployed in the space where thermal comfort is needed (Veselý and Zeiler, 2014). It is configured to fit individual needs and have been tested with good energy efficiency results (Kaczmarczyk et al., 2010; Pasut et al., 2013; Zhai et al., 2013), especially for residential building (Veselý and Zeiler, 2014). However, in recent years, increasing studies start to focus on using personal thermal comfort to solve general comfort problems (Jiang and Yao, 2016; Kim et al., 2017; Qianchuan Zhao et al., 2014). Instead of just modelling within individual level, personal thermal comfort could also be used as a foundation to simulate behavioural-based human interaction and applied to building energy management system (Jiang et al., 2017). But before building extraordinary model, it is necessary to carefully think about why we need personal comfort model and how to scale it.

2.1. PMV and Adaptive Model

PMV and adaptive model are still two main models used in thermal comfort. PMV is made based on static steady laboratory experiment by Fanger in 1970 and widely applied in HVAC buildings around the world. However, there are many studies shows that PMV underestimate or overestimate occupant's thermal sensation. In the contrast, in adaptive model, occupants are treated as active agents which could interact with surround environment instead of just a passive receiver (Brager and de Dear, 1998). Compared with PMV, people should have more power to dominate the thermal environment within a certain level, except when weather variations exceed the thermal threshold human could control. However, there is still controversy between PMV and adaptive model. Because PMV still serves well for HVAC system building and adaptive still have quite a lot limitation when apply it in the real world. Many studies focus on how to compare PMV with adaptive model in different building types, countries, applied to different people with various age, nationality and gender. These really help researchers build a better worldwide database, but it is time to rethink what kind of thermal comfort model could succeed simulating person's adaptive thermal comfort.

Based on the concept of self-regulating thermal comfort system (Nicol and Humphreys, 1973) and adaptation feedback loop (De Dear et al., 1998), within indoor environment and ignore any potential factors such as lighting, acoustic and material factors, the entire thermal regulation system could be generally described in Figure 1:

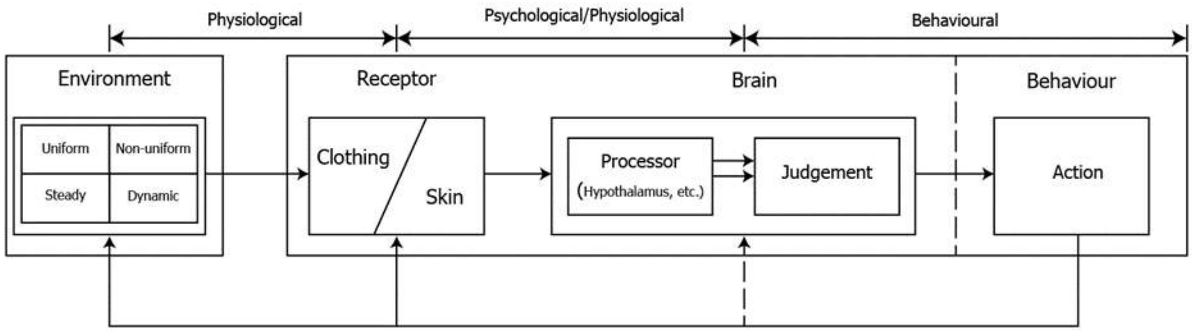


Figure 1. Thermal regulation system

From the environment which decides occupant's initial objective conditioning level, the physical cognition signal is produced on receptors (generally skin or clothes) and transport to the hypothalamus. Different kinds of receptors or sensors embedded under the skin and tissue give people the ability of passing the perception information. This is how perceived information transformed from external to internal. When hypothalamus got the information, it will deliver the electrical impulse to different lobes in the brain to process the signal and form a general judgement. Fanger's work is mainly explained the relationship between the perceived information and the judgement result. However, adaptive process covers more parts. When you have a judgement, you may/may not have an action which expressed by behaviours to change current environmental. It could be a gesture which turn-on the air conditioner to make yourself cooler (response to environment), an action that put on a jacket to make yourself little warmer (response to receptor) or a period of silence which make yourself calm down (response to brain). The systematic running of these four modules could generate a complete thermal sensation feedback loop, a "reflex arc".

In general, studies always like to talk about PMV model and adaptive model separately. However, if we systematically analysed them from the process that how information was transferred through this "human" and "environment" feedback cycle, PMV and adaptive model are not quite "different". In our view, there is not absolute right or wrong between adaptive and PMV model. It could be treated as a "scale" problem in thermal regulation system. PMV model mainly focus on exploring the configuration which linking environment, receptor and brain while adaptive model considers the entire cycle system which includes the feedback influence of behaviour. They have different scales and result, but within the same logical cycle. In addition, to personal comfort model, it proves that in the view of physiology, each person has a unique feedback loop process based on physical neural network.

2.2. narrow and broad sense of personal thermal comfort

In this feedback loop, the personal thermal regulation system is influence by many factors from psychology, physiology and behaviour, the term "personal" could also be defined by narrow and broad sense. The narrow-sense personal model is just a thermal comfort model for a single person within a certain area, or we could call it a private room. There is no any other people in that space to indirectly interact with and the model is only built for this person. The place could be in a bedroom, a capsulated office room etc. In contrast, the common-sense personal model is built in a more complex environment, with surrounding people, with social interaction and dynamic context, where the other factors all may influence the assessment of a person's thermal comfort. For instance, assuming there is a thermal comfort field study that conducted in an office building with 20 subjects. During three weeks' study, each subject need to finish questionnaires three times a day. Subjects work together in the same office; their context and cognition have been interacted with each other. Although finally each subject still got amount of data, this data is just a broad-sense personal data. If want to get narrow-sense personal data, each subject should be simultaneously isolated in a similar office.

Most of the field studies don't carefully pay attend to the difference between narrow-sense and broad-sense setting. As a result, it is better to separate these two types of personal concept in real studies. Because it is always difficult to represent broad-sense personal thermal comfort under the influence of context and following cognition variation. Starting from narrow-sense personal thermal comfort and then apply to different scenarios could be the key to fundamentally quantify and validate the adaptive process in real field study.

2.3. Individual difference

Individual difference is commonly referred in psychology studies, especially in differential psychology. Psychology is a study of individuals, but modern psychologists often study groups, or attempt to discover general psychological processes then apply to all individuals. They always treat variation as error rather than take it as interesting phenomena to study. But the fact is that there are significant variations between individuals and it is important when we want to explain how variant behaviour differ.

In comfort study, behaviour adjustment, physiological acclimatization and psychological habituation are three sections which produce huge influence on adaptive process. There are some studies (Gauthier and Shipworth, 2015; Wei et al., 2010) summarise which kinds of behaviours that occupants more likely to engage. But there are still huge sampling error and applicability to generalize those methods to comfort studies. A common method during their field study is increasing personal interest to achieve more meaningful analysis. In addition, personal comfort model is a dynamic process. There are much valuable details are missing in conventional comfort field study. In order to take care of all these factors, increasing personal interest is a good way to generalize more accurate data for specific comfort studies.

2.4. Rapid growing technology

Personal thermal comfort model also brings a question that "Are current sensors and questionnaire technology possible to measure such increasing personal interest?" Personal comfort measurement not only require environment, body, perception and behaviour data, but also need to collect all these data simultaneously, accurately and efficiently. Compared with widely used data logger, handheld sensors or different kinds of digital questionnaires, to accomplish personal thermal comfort measurement require a high-level facility which could be a big automation challenge. In recent years, there appear several advanced data collection tools which take advantage of new technologies such as Bluetooth Low Energy (BLE), hub or mobile app (Gao and Keshav, 2013; de Dear et al., n.d.; Zhao et al., 2017). Instead of conducting repetitive studies on changes in thermal sensation, these new data collection methods could easily track real-time environment data, thermal responses and adaptive behaviour. It is not only a challenge for researchers, but also a job for engineers to develop new measurement sensors with reliable calibration method.

3. PTC Framework

The framework for Personalised Thermal Comfort (PTC) model is based on the principle that each person has their unique dynamic comfort model. As personal comfort data could be treated from common or narrow sense, this framework focus on narrow-sense personal modelling, which keeps the subject away from psychological or behavioural influence from other people. Figure 2 illustrate how personal thermal comfort framework works.

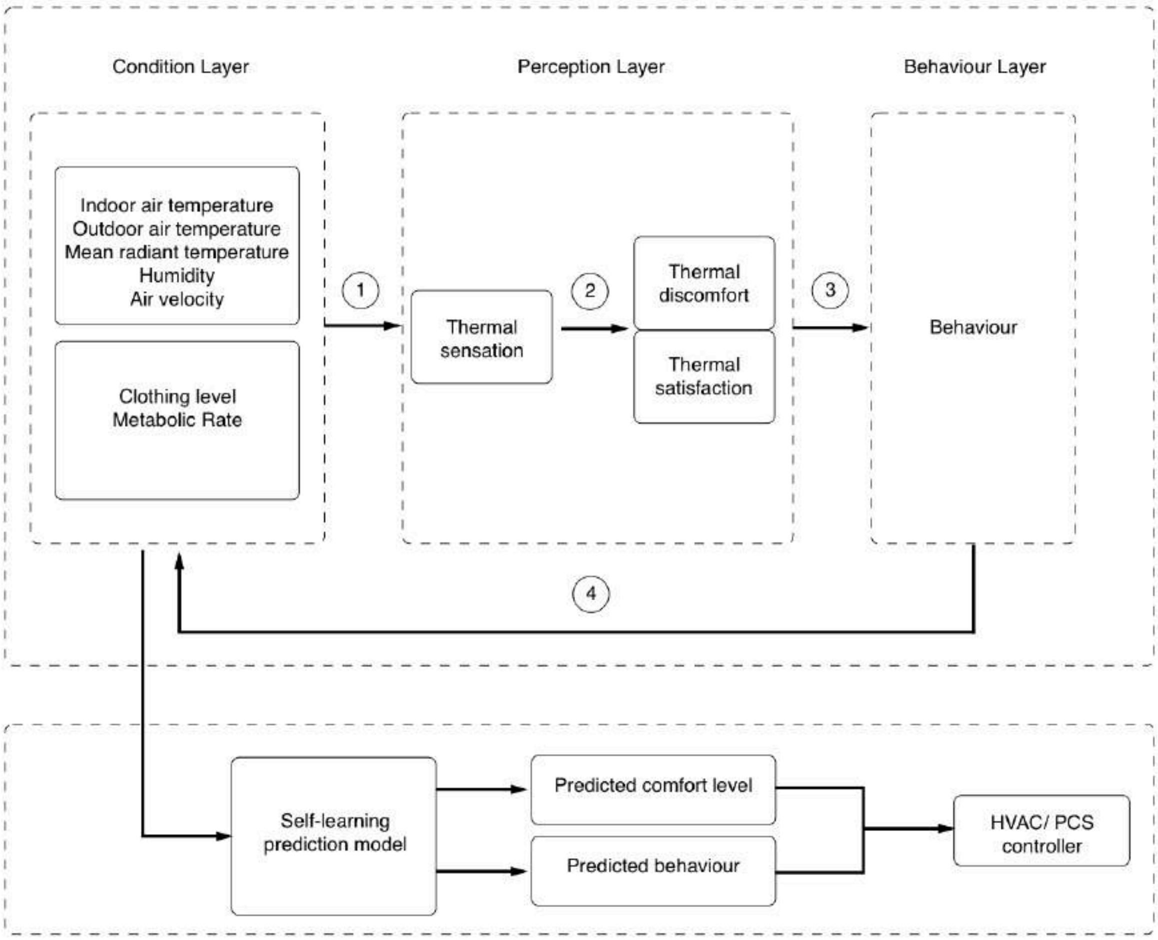


Figure 2. Self-learning framework for personalised thermal comfort (top), self-learning implementation in HVAC/PCS system (bottom)

In PTC framework, there are four steps, or so called four functions. Firstly, perception function. The environment data including outdoor air temperature and personal data which considered as “Condition Layer” are perceived by skin receptor and produced initial thermal sensation. Secondly, habituation/acclimatization function. Any factors including subject’s previous experience, genetic reason, stress could be counted into this function. As there are so many possible ways to systematically arrange this function, this framework treat thermal sensation, discomfort and satisfaction as a whole system which named as “Perception Layer”. Thirdly, behaviour function. From the thermal perception and “attitude” that subject produced, they may or may not conduct corresponding adaptive behaviours. Finally, feedback function. The feedback from the adaptive behaviour will re-influence environmental condition such as opening the window or change personal condition by take on/off clothes until the subject feels neutral or remain at a certain level. For instance, the subject was sitting in his room. But he felt a lit bit warm (perception function). He was not satisfied with current thermal environment (habituation/acclimatization function). So he took off his sweater (behaviour function) and feel much better (feedback function + perception function + habituation/acclimatization function). In addition, if the prediction result of thermal perception and behaviour could be communicated with PCS or HVAC controller. The system will not only give suggested temperature setting based on comfort level, but also considering behaviour change as another option.

To quantify these four steps, it is necessary to clarify which method to use. First, as all the variables in each layer are discrete, the relationship between each layer could be treated as a classification problem. Second, instead of traditional statistics method which based on average data, learning algorithms, especially machine learning algorithms are used in personal adaptive process to deal with individual difference. Finally, depending on the difficulty or research topic you want to achieve, swiftly simplify the variables in each layer. For instance, habituation/acclimatization function contain so much context to control. As a result, we could just use thermal sensation to represent perception layer. Figure 3 shows the details of this learning process:

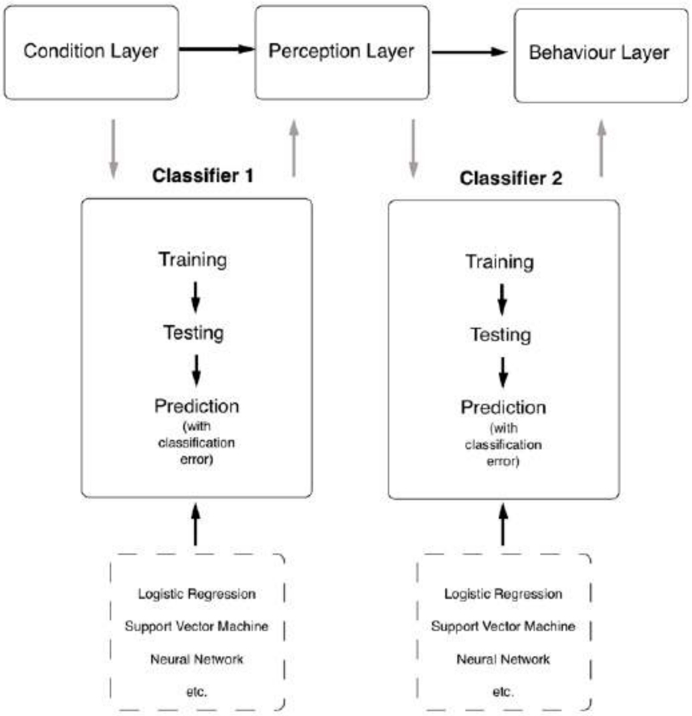


Figure 3. Machine learning process between three layers

Our approach is based on two supervised machine learning steps: “Condition Layer” to “Perception Layer” and “Perception Layer” to “Behaviour Layer”. The logic in these two steps is the same: data import, data training, data testing and finally got a prediction result with its unique error. In each step, different machine learning algorithms will be tested and the best algorithm which achieve the best prediction result with low error will be selected. This also means the final selected algorithm in each step for each subject may not be the same. Finally, each subject will get a unique personalised prediction model which predict his thermal sensation and potential adaptive behaviour.

4. Methods

4.1. Data collection tool

ASHARAE 55 provides a reliable sensors standard for researchers to follow. However, on the market, it is difficult to find a sensor which could cover air temperature, mean radiant temperature, humidity and air speed at the same time. In reality, most of the researchers still put these sensors together and manually record the data and switching different sensor one by one always increase measurement error during real field studies. Some companies or institution could develop this as an all-in-one device, but it cost so much money and the final products are always not quite open to the public. At the moment, one of the most common way to take measurement is still data logger and these sensors lack of connection properties such as Wi-Fi or Bluetooth to provide real-time distance monitoring. Thermal comfort study need a cheap, reliable, open-sourced, smart-connected sensor to conduct more accurate and efficient field study. This paper introduces Smart Thermal Comfort (STC) sensor box (Figure 4).

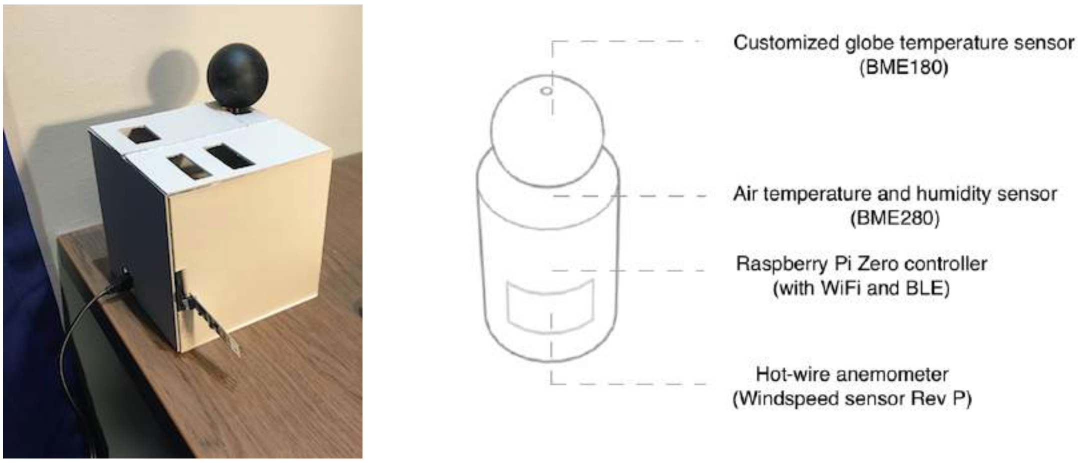


Figure 4. STC sensor box (left) and internal core sensors (right).

STC sensor box is an open-sourced thermal comfort measurement tool. You could visit our GitHub page (https://github.com/jayingq/Smart-Thermal-Comfort-System) to get latest news. First, the sensors are all benchmarked and tested from the current existing sensors on the market. Second, in order to help researchers conduct their own thermal comfort studies, all the source codes of STC are open-sourced (MIT licenced) which means anyone could buy the sensors on the market and make their own measurement tool. Finally, specific sensor settings in the STC systems are totally controllable. The minimum measurement interval could be set as 5s and there is no max limit. In addition, there are many open-sourced libraries (packages) on the Internet which could help you add more function. Table 1 shows the details of the sensors used in STC sensor box:

Table 1. Sensors specifications

Environment parameters	Range	Accuracy
Air temperature (BME280)	-40C° to 85C°	±0.5C° (calibrated)
Globe temperature (BME180)	-40C° to 85C°	±1C° (max)
Relative Humidity (BME280)	0% to 100%	±3%
Wind speed (Wind Sensor Rev P)	0 to 30 m/s	±5% (calibrated)

When the measurement begins, all the data will store in its SD card by CSV file and simultaneously uploaded to our database by Wi-Fi.

4.2. Digital questionnaire

A cheap, all-in-one and open-sourced sensor box is not enough for a well automated data collection system. Based on EdenApp (Zhao et al., 2017), we developed STC app, an mobile application (currently only support Apple device) to conduct thermal comfort digital survey. Instead of paper-based or web-based traditional medium, occupants could use their smart phone, the app to finish all the questionnaire.

Firstly, to improve efficiency, we add experience sampling function. In conventional thermal comfort survey, subject always need to follow the daily goal, such as finish the questionnaire three/four times a day or fill it in the morning, lunch and after dinner. This kind of survey usually take several months or a year to gather enough data. However, there are still many interesting points are missing during the measurement. Figure 5 shows a simple temperature and humidity measurement of a student's accommodation room. If just like a conventional survey which take three times a day on fixed time, it is difficult to detect the dynamic thermal variation marked as red circle.

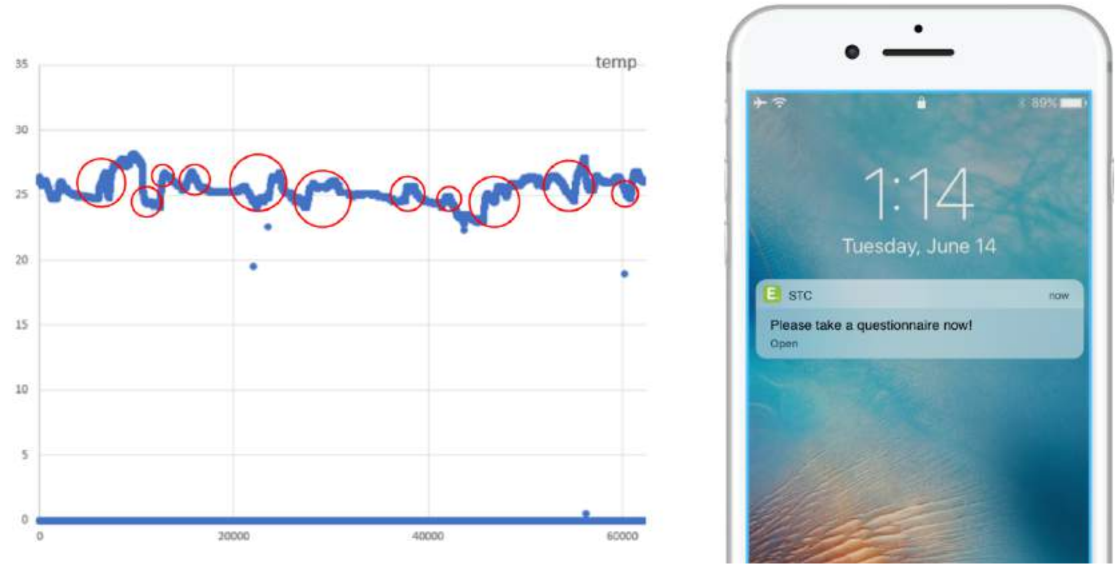


Figure 5. Air temperature variation in a student's accommodation in Edinburgh (left); Notification in STC app (right).

With experience sampling method in STC app, when the temperature in the past ten minutes changed about 0.5 degree (customizable), the app will automatically send notification to the user to take questionnaire. Moreover, ten minutes later, the app will send another notification suggesting subjects to take another questionnaire to examine their corrected thermal sensation and preference. It will really help both researchers and occupants make their work more efficient. Secondly, user-based mobile app could give occupants a more natural way to express their thermal sensation and increase completion rate of the survey. According to our pilot study, it generally takes no more than 30s to finish a questionnaire. Figure 6 illustrates the workflow of the STC app and Table 2 shows the thermal perception and behaviour data collected from the app.

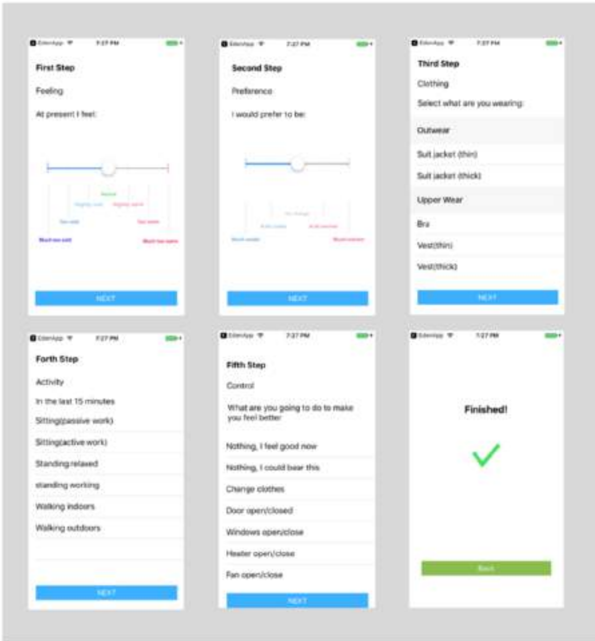


Figure 6. STC App user interface (the latest version may be updated on our GitHub page)

Table 2. Thermal perception and behaviour data collected from STC App

Information	Reference	Scale	Range
Thermal sensation	7-scale thermal sensation vote	1	From -3 to +3: Cold (-3), Cool (-2), Slightly cool (-1), Neutral (0), Slightly Warm (+1), Warm (+2), Hot (+3)
Thermal preference	(Nicol et al., 2012)	1	From prefer much warmer (+2) to much cooler (-2)
Thermal satisfaction	5-point satisfaction scale	1	From very satisfied (+2) to very dissatisfied (-2)
Adaptive behavior	(Wei et al., 2010; Gauthier and Shipworth, 2015)	/	Nothing (0), change clothes (1), adjust door/windows (2), adjust thermal control (3), have food/drink (4), change location/room (5), other (6).

Finally, as ethical problem and data management system, the app cannot upload to App store, but we make it open-sourced and all the source code is available on our STC GitHub page. You can download the source code, customize the app based on your project and run it on your iPhone or iPad.

4.3. Learning Algorithms

After getting all these data, within the framework, how to choose the best learning algorithms decide the final prediction accuracy of the entire model. There have been an increasing amount of study using machine learning algorithm to predict thermal comfort (Kim et al., 2017; Chaudhuri et al., 2017; Jiang et al., 2017; Jiang and Yao, 2016). However, all of them just focus on how to predict thermal sensation vote, but ignore the importance of adaptive behaviour which because of lack of related data on current comfort database. There are many learning algorithms which could be used to build personal thermal comfort model and they always achieve great results. In this section, we simply introduce three of the most commonly used supervised machine learning algorithm for thermal comfort:

a. Logistic Regression
   Logistic Regression is a statistical method dealing with the situation when there are multiple inputs with one outcome. It computes a weighted sum of the input data and uses sigmoid function to output a number between 0 and 1 which stands for its probability. For instance, in personal thermal comfort modelling, thermal sensation is presented by seven scales from -3 to 3. By training seven binary classifiers for each set of input data, Logistic regression could give each scale a probability. Rank the probability list and the best prediction result (sensation level) could be selected.
b. Support Vector Machine (SVM)
   SVM is another commonly used machine learning algorithm for classification. It builds a hyperplane to separates different classes. Meanwhile, to avoid the model over-sensitive to original data, soft margin classification is suggested. By adjusting hyperparameter C to limit margin violation, it could help make fewer prediction error.
c. Artificial Neural Networks (ANN)
   ANN is based on the human biological neuron networks, wherein signals are transported between millions of connected links. The weighted neuron and links perform programmed function to determine output signal. In fact, ANN suite for project which has very large data size and huge complexity. But some studies used it to analyse thermal comfort problem and it may be widely used when there are more data coming in the future. For instance, Chaudhuri (2017) built a two-layer feed forward ANN, with sigmoid function as activation function for hidden and output neurons.

5. Discussion and Conclusion

This paper presents a novel self-learning framework for building personalised thermal comfort models. To simulate personal adaptive process in comfort modelling, STC data collection tool including sensor box and mobile app are developed depending on accuracy, cost, customizability and efficiency. As an open source project, STC data collection tool is a good start to combine digital sensors and smart questionnaire to capture more detail under different scenarios. With more data and reasonable field study setting, it could help researchers better understand adaptive model from personal level and build better prediction model for building energy system.

Personal thermal comfort model is a good start to conduct “ground-up” comfort simulation. In most buildings, space is occupied by multi-users. But narrow-sense personal model only suite for space like accommodation, hotel or personal office, or for PCS. Thermal comfort standard such as existing PMV or adaptive model consider most people’s profit, instead of a space with only one person. In fact, personal thermal comfort is the first step to build a full personal comfort profile. Based on this data, how each occupant interacts with each other and how comfort preference varied could be quantified in multi-user space. Figure 7 illustrate how self-learning framework could be used in multi-user space by Agent Based Modelling (ABM). Each subject could be treated as an agent with their own property and function and these functions influence how agents interact with each other. It is a big challenge to model each agent (Jiang et al., 2017) and hope this personalised thermal comfort self-learning framework could help build the foundation of this complex simulation.

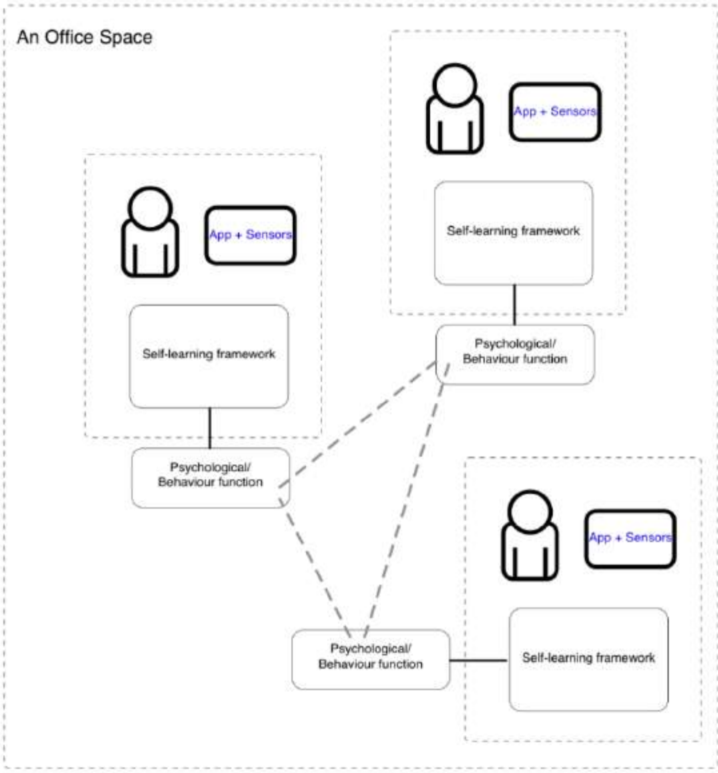


Figure 7. Thermal comfort interaction and variation in multi-user space (office)

In the future, there are a lot of work to do based on personalised thermal comfort to better understand human thermal adaptive process:

a. By tracking the same group of people, find out whether or how building types influence personalised thermal comfort.

b. Conduct the field study with more subjects.

c. By using more dynamic environment setting to increase prediction range of comfort level and behaviour.

d. Try ABM to simulate and validate how personalised thermal comfort vary in a social context.

6. References

Auffenberg, F., Stein, S. and Rogers, A., 2015, A personalised thermal comfort model using a Bayesian network.

Brager, G.S. and de Dear, R.J., 1998, Thermal adaptation in the built environment: a literature review. *Energy and Buildings*, 27(1), pp.83–96.

Chaudhuri, T., Soh, Y.C., Li, H. and Xie, L., 2017, Machine learning based prediction of thermal comfort in buildings of equatorial Singapore. *Smart Grid and Smart Cities (ICSGSC), 2017 IEEE International Conference on*. 2017 IEEE, pp. 72–77.

Daghigh, R., Adam, N.M. and Sahari, B.B., 2009, Ventilation parameters and thermal comfort of naturally and mechanically ventilated offices. *Indoor and Built Environment*, 18(2), pp.113–122.

de Dear, R., Parkinson, T. and Parkinson, A., Pervasive and real-time Indoor Environmental Quality (IEQ) monitors.

De Dear, R.J., Brager, G.S., Reardon, J. and Nicol, F., 1998, Developing an adaptive model of thermal comfort and preference/Discussion. *ASHRAE Transactions*, 104, p.145.

Deuble, M.P. and de Dear, R.J., 2014, Is it hot in here or is it just me? Validating the post-occupancy evaluation. *Intelligent Buildings International*, 6(2), pp.112–134.

Fanger, P.O., 1970, Thermal comfort. Analysis and applications in environmental engineering. *Thermal comfort. Analysis and applications in environmental engineering.*

Gao, P.X. and Keshav, S., 2013, SPOT: a smart personalized office thermal control system. *Proceedings of the fourth international conference on Future energy systems*. 2013 ACM, pp. 237–246.

Gauthier, S. and Shipworth, D., 2015, Behavioural responses to cold thermal discomfort. *Building Research & Information*, 43(3), pp.355–370.

Humphreys, M.A., 1978, Field studies of thermal comfort compared and applied. *Energy, heating and thermal comfort: practical studies from the building research establishment*, pp.237–265.

Jazizadeh, F. et al., 2013, Human-Building Interaction Framework for Personalized Thermal Comfort-Driven Systems in Office Buildings. *Journal of Computing in Civil Engineering*, 28(1), pp.2–16.

Jiang, L. and Yao, R., 2016, Modelling personal thermal sensations using C-Support Vector Classification (C-SVC) algorithm. *Building and Environment*, 99, pp.98–106.

Jiang, L., Yao, R., Liu, K. and McCrindle, R., 2017, An Epistemic-Deontic-Axiologic (EDA) agent-based energy management system in office buildings. *Applied Energy*, 205(Supplement C), pp.440–452.

Kaczmarczyk, J., Melikov, A. and Sliva, D., 2010, Effect of warm air supplied facially on occupants' comfort. *Building and Environment*, 45(4), pp.848–855.

Kim, J. et al., 2017, Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning. *Building and Environment*.

Liu, W., Lian, Z. and Zhao, B., 2007, A neural network evaluation model for individual thermal comfort. *Energy and Buildings*, 39(10), pp.1115–1122.

Nicol, F., Humphreys, M. and Roaf, S., 2012, *Adaptive thermal comfort: principles and practice*, Routledge.

Nicol, J.F. and Humphreys, M.A., 1973, Thermal comfort as part of a self-regulating system.

Pasut, W. et al., 2013, Effect of a heated and cooled office chair on thermal comfort. *HVAC&R Research*, 19(5), pp.574–583.

Veselý, M. and Zeiler, W., 2014, Personalized conditioning and its impact on thermal comfort and energy performance – A review. *Renewable and Sustainable Energy Reviews*, 34, pp.401–408.

Wei, S., Buswell, R. and Loveday, D., 2010, Probabilistic modelling of human adaptive behaviour in non-airconditioned buildings. *Adapting to Change: New Thinking on Comfort. Cumberland Lodge, Windsor, UK, Network for Comfort and Energy Use in Buildings*.

Yang, W. and Zhang, G., 2008, Thermal comfort in naturally ventilated and air-conditioned buildings in humid subtropical climate zone in China. *International Journal of Biometeorology*, 52(5), pp.385–398.

Zhai, Y. et al., 2013, Comfort under personally controlled air movement in warm and humid environments. *Building and Environment*, 65, pp.109–117.

Zhao, Q. et al., 2014, A data-driven method to describe the personalized dynamic thermal comfort in ordinary office environment: From model to application. *Building and Environment*, 72, pp.309–318.

Zhao, Q. et al., 2014, A data-driven method to describe the personalized dynamic thermal comfort in ordinary office environment: From model to application. *Building and Environment*, 72, pp.309–318.

Zhao, Y., Uduku, O. and Murray-Rust, D., 2017, *EdenApp Thermal Comfort: An mobile app for measuring personal thermal comfort*,

Zhao, Y., Zhang, H., Arens, E.A. and Zhao, Q., 2014, Thermal sensation and comfort models for non-uniform and transient environments, part IV: Adaptive neutral setpoints and smoothed whole-body sensation model. *Building and Environment*, 72, pp.300–308.

Dynamic Decision and Thermal Comfort: CFD and Field Test Analysis of a Personalised Thermal Chair

Sally Shahzad[1], John Kaiser Calautit[2], Ben Richard Hughes[3]

[1]Department of Mechanical Engineering and the Built Environment, University of Derby, Derby, DE22 3AW, UK sally.shahzad@gmail.com

[2]Faculty of Engineering, University of Nottingham, NG7 2RD, UK

[3]Department of Mechanical Engineering, University of Sheffield, S10 2TN, UK

Abstract: The dynamic aspect of thermal comfort is overlooked in research, resulting in the aim to provide a steady thermal environment to satisfy the occupants. In this study, the thermal decision (combination of thermal sensation and preference) of the occupants were measured before and after providing localised personal control of a thermal chair in the workplace. Field test studies of thermal comfort (environmental measurements and survey questionnaires) were followed by a numerical modelling of the thermal performance of the thermal chair with heated seat and backrest using the commercial Computational Fluid Dynamics (CFD) tool FLUENT17. The 3D steady Reynolds-averaged Navier–Stokes equations were solved in combination with the k-ε turbulence model. The effect of varying the seat and back rest temperature settings (low, medium and high) on Predicted Mean Vote (PMV) at different locations were investigated. Overall, the results indicated that thermal decision of the occupants is dynamic and it is subject to change. This study suggests the application of localised personal control of the thermal environment in order to provide thermal comfort. In this way, the occupant can find their own comfort at any given time according to their immediate and dynamic requirements. The implication of this finding needs to be considered as part of the environmental design of a building.

Keywords: Neutral thermal sensation, dynamic, thermal chair, thermal comfort, CFD

1. Introduction

'Neutral thermal sensation' is the main measure to assess thermal comfort of the occupant (Voelcker, 2002), which the PMV model and most studies apply (Zhang et al, 2011, Kwong et al, 2014). Although some researchers questioned the reliability of neutral thermal sensation in assessing thermal comfort (Humphreys and Hancock, 2007, Shahzad, 2014), still the main stream of the current research is based on a neutral thermal feeling of the occupant (Shahzad, 2014), such as the work of (Liu et al, 2012, Cigler et al, 2012, Van Marken and Kingma, 2013, Schellen et al, 2013). In other words, the current measure of thermal comfort is whether or not the occupant has a neutral thermal sensation regarding the surrounding thermal environment (Fanger, 1970, ASHRAE, 2013) meaning neither cold nor hot (Hawkes, 2002). Both adaptive and PMV (Predicted Mean Vote) models are based on thermal neutrality. The ASHRAE (2009) seven point thermal sensation scale (presented in Table 1) is the most commonly used survey method to assess thermal comfort (Shahzad, 2014). The PMV model is the main method of assessing thermal comfort and it is set based on thermoneutrality (Van Hoof, 2008). Many studies question the reliability of the PMV model (Van Hoof, 2008, Shahzad, 2014, Ioannou and Itard, 2017). Van Hoof (2008) states that 'direct measures of thermal satisfaction and acceptability are not incorporated in the current PMV model' (Van Hoof, 2008). Many studies still mainly rely on the PMV model to assess thermal comfort of the occupant, such as in Japan (Takasou et al, 2017). It is assumed that when the respondent feels neutral regarding the surrounding thermal environment, they are thermally comfortable and thus, that thermal environment is considered as comfortable. In case, the occupants respond variations of warm or cold rather than neutral, the thermal environment is assumed as uncomfortable and measures are expected in place to re-gain the thermal neutrality of the occupants. Accordingly, many researchers looked for the optimum temperature that the majority of the occupants feel neutral. The comfort zone, which is a range of acceptable thermal conditions (relative humidity, radiant and dry bulb temperature), is also produced according to the neutral thermal sensation (ASHRAE, 2013). 'Acceptability is determined by the percentage of occupants, who have responded neutral or satisfied with their thermal environment' (ASHRAE, 2009). In fact, the ASHRAE handbook (2009) goes one step further in frequently replacing thermal comfort with thermal neutrality. Thermal neutrality has been used by other researchers, such as in the work of McCartney and Nicol (2002) and the definition of thermal comfort (Hawkes, 2002, Brenglmann and Savage, 1997).

Table 1: The ASHRAE seven point scales (ASHRAE, 2009)

Thermal sensation						
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Thermal preference						
Much cooler	Cooler	Slightly cooler	No change	Slightly warmer	Warmer	Much warmer
Comfort						
Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Comfortable	Very comfortable
Satisfaction						
Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied

2. Previous Related Work

Studies show that thermal control increases user thermal comfort (Shahzad et al, 2017). Personalised comfort models are recommended in a "human-centric approach" of designing comfortable and energy efficient buildings (Kontes et al, 2017). Personalised and localised heating were found to have a significant impact on improving thermal comfort (Deng et al, 2017). Fojtlín et al (2017) investigated thermal comfort of a car cabin using thermal sensors on the backrest and seat as well as a thermal manikin. Kim et al (2018) introduce a "personal comfort model", as a machine learning system to predict thermal comfort of the occupant. Several studies researched the performance of a thermally controlled office chair, as illustrated in Figure 1 (Kogawa et al, 2007, Watanabe et al, 2009, Zhao et al, 2016), as demonstrated in Figure 1. Mainly, ventilation and cooling performances of the chair were researched rather than heating. Ventilation was studied through the application of fan/vents on armrests (Kogawa et al, 2007), back and seat (Watanabe et al, 2009, Zhao et al, 2016). In some studies, separate control systems were provided for back and seat of the chair (Watanabe et al, 2009). Zhao et al (2016) added heating elements to the back and seat fans to allow the chair to be used for both cooling and heating. Zhang et al (2007) used a water tubes for both heating and cooling purposes. Heated and cooled seats have been used in the car industry (Parkhurst and Parnaby, 2008). Although research on the heating application of the office chair is not thoroughly investigated, it is suggested that the heating application of the office chair is more effective than cooling (Mao et al, 2017). In most studies concerning the thermal chair, mainly experimental chambers are used. The lack of context (Nicol and

Humphreys, 1973) and the difficulty that the findings may not apply to the context of real life (de Dear, 1994) are some of the limitations of the climate chambers.

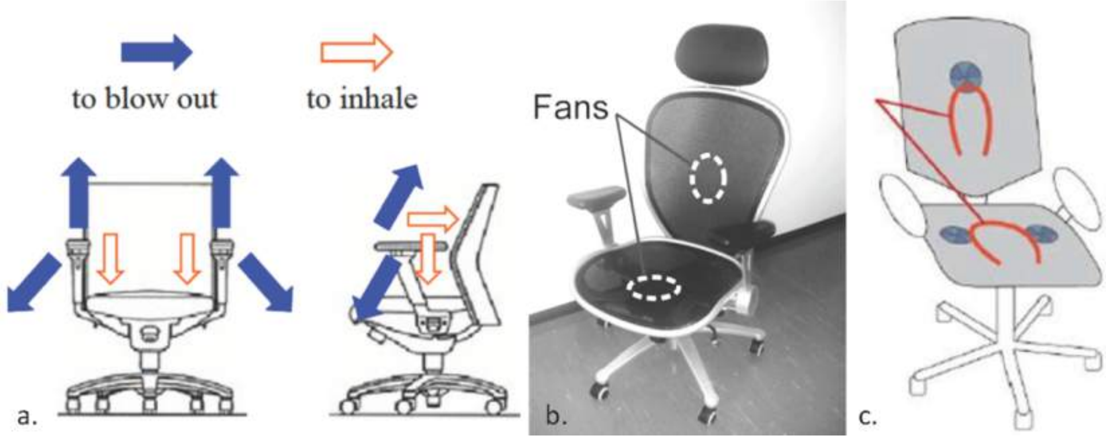


Figure 1. Thermal chairs studied by a. Kogawa et al (2007) b. Watanabe et al (2009) c. Zhao et al (2016)

3. Research Methods

Shahzad (2014) uses thermal decision to measure thermal comfort of the occupants. Thermal decision is a combination of thermal sensation and thermal preference. Thermal decision considers both the current status of the occupant (thermal sensation) as well their desire to change the temperature (thermal sensation). For example, in case the occupant feels slightly warm but wants no change, their thermal decision is considered as slightly warm, meaning they are happy to feel slightly warm. In this study, users' desire and thermal decision were measured when a personalised comfort system was provided for them. The changes of the thermal decision as well as occupants' desire for a neutral thermal sensation were examined. The application of a thermal chair equipped with separate temperature controls for the back and seat of the chair was investigated in an open plan office. Thermal decision as well as thermal sensation, preference, comfort, and satisfaction of the respondents and the environmental measurements before and after using the chair were recorded. Forty four doctoral students and research staff in the University of Leeds used the chair in 2014. The participants were between twenty to forty years old and included fifteen females and nineteen males. The results were compared to the CFD computer simulation of the thermal performance of the chair.

Figure 2. Thermal Chair, designed for this study

In order to simulate the velocity and temperature distribution around the chair with heated seat and backrest with a manikin, the commercial Computational Fluid Dynamics (CFD) tool FLUENT17 was employed. The 3D steady Reynolds-averaged Navier–Stokes equations were solved in combination with the k-ε turbulence model. The k-epsilon transport model was employed due to its well-documented performance in simulating indoor airflows. The SIMPLE algorithm was employed for pressure velocity coupling, pressure interpolation was second order and second order discretisation schemes were used for both the convection terms and the viscous terms of the governing equations. The general governing equations include the continuity, momentum and energy balance for each individual phase. Convergence was assumed to be obtained when all the scaled residuals leveled off and reached a minimum of 10^{-6} for x, y momentum, and 10^{-4} for k, ε and continuity. A computational domain was created around the thermal chair with a seated manikin. The domain has an inlet on one side which was set to 0.1 m/s (velocity) and 23˚C (temperature) and pressure outlet on the opposite side with the thermal chair located at the centre of the domain. The thermal chair had a heated seat and back rest with an initial heat flux of 40W/m^2. A non-uniform mesh was applied to volume and surfaces of the computational domain. In this study, a grid-sensitivity analysis is carried out to reduce the discretisation errors and the computational time. It was performed by conducting additional simulations with same domain and boundary conditions but with various mesh sizes a coarser grid and a finer grid. The results showed a limited dependence of the air velocity results on the grid resolution. The mean error between the fine and coarse mesh was 5.40% or ±0.032 m/s.

4. Results and Analysis

Figure 3 displays a cross-sectional temperature contour along the computational domain with the thermal chair and seated manikin. The results detail the temperature distribution around the thermal chair which indicated the seat and back rest locations having a significantly higher temperature (28-36˚C) than the rest of the locations. As expected, lower air temperature can be observed near the face and feet area (22.5-24.5 ˚C) because of the absence of heating in these locations and higher airflow movement. Higher temperature can be observed near the seat area and thigh region due to lower air movement and constrained space. Clearly, the seat and back rest regions had different temperature levels and hence could impact the overall thermal comfort distribution of the user. The results indicated the necessity of separate control systems for the seat and the back which was implemented in the design of the thermal chair. To investigate the impact of various temperature settings on thermal comfort distribution, seven different configurations were simulated (Figure 4): low settings for both back rest and seat, medium settings for both back rest and seat, high settings for both back rest and seat, low settings for back rest and medium for seat, medium back and low seat, medium back and high seat and high back and medium seat. Thermal comfort levels calculated using PMV method with set values for humidity (30%), metabolic rate (1 met), clothing (0.7). Based on the PMV predictions, only the first configuration with both low settings for the seat and backrest area was able to provide acceptable comfort levels (below +/- 0.5 PMV) for all the locations. Increasing the setting to medium and high will clearly increase the PMV to +1 slightly warm and +2 warm levels for both the seat and backrest area.

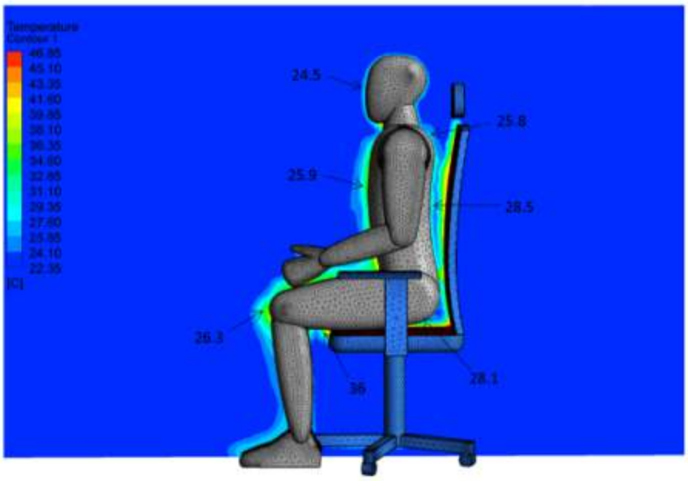


Figure 3. Temperature distribution around a manikin with the thermal chair. Shahzad (2017)

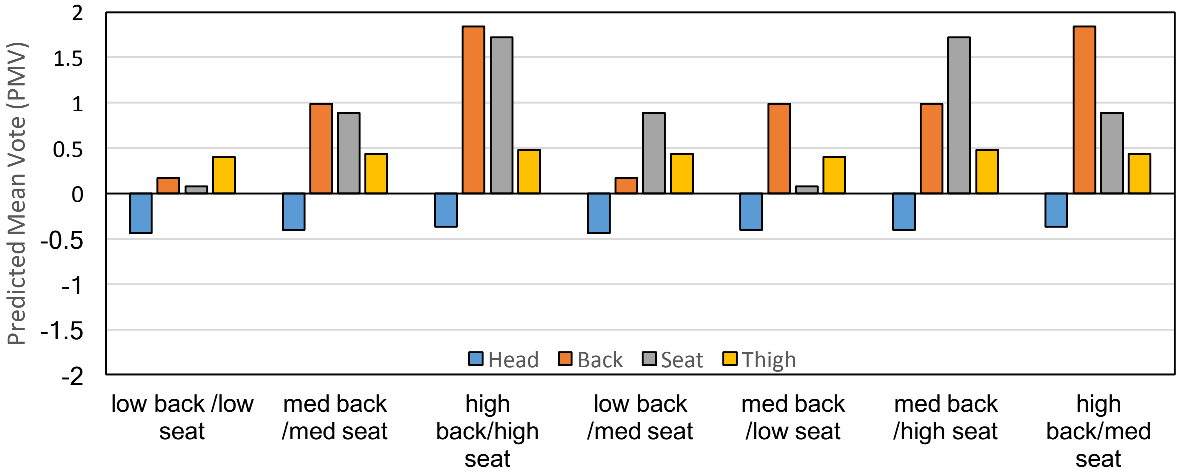


Figure 4. Effect of varying the seat and back settings (low, medium and high) on Predicted Mean Vote at different locations.

As both thermal sensation and thermal preference are important in assessing thermal comfort, in this study a combination of the two is used as thermal decision, as shown in Figure 3 (Shahzad, 2014). Before using the thermal chair, fifteen respondents felt neutral (thermal sensation), but six of them wanted a change in the temperature (they had a slightly warmer to much warmer thermal preference). Meaning nine respondents had a neutral thermal decision before using the chair. Overall, twenty users (out of forty four) had a neutral thermal decision. In five cases the respondents felt slightly cool and wanted to feel slightly warmer, while five users felt slightly warm and wanted to feel slightly cooler. One user felt coll and wanted to feel warm.

After using the thermal chair, only seven users had a thermal decision to feel neutral. Three respondents felt neutral (thermal sensation) and wanted no change (thermal preference). One participant felt slightly cool and preferred slightly warmer, while two users felt slightly warm and preferred slightly cooler. One user felt warm and preferred to feel cooler. Overall, comparing the results before and after using the chair, only five participants were consistent in their decision to feel neutral, which are demonstrated with a green cross on Figure 3. Twenty two respondents did not want to feel neutral (thermal decision) either before or after using the chair. Overall, thirty nine respondents (89%) wanted to feel other than neutral either before or after using the thermal chair. Also overall, only nine participants (20%) had a consistent thermal decision throughout the study. In sixteen cases, the changes of thermal decision was more than one level (e.g. from neutral to warm) before and after using the chair.

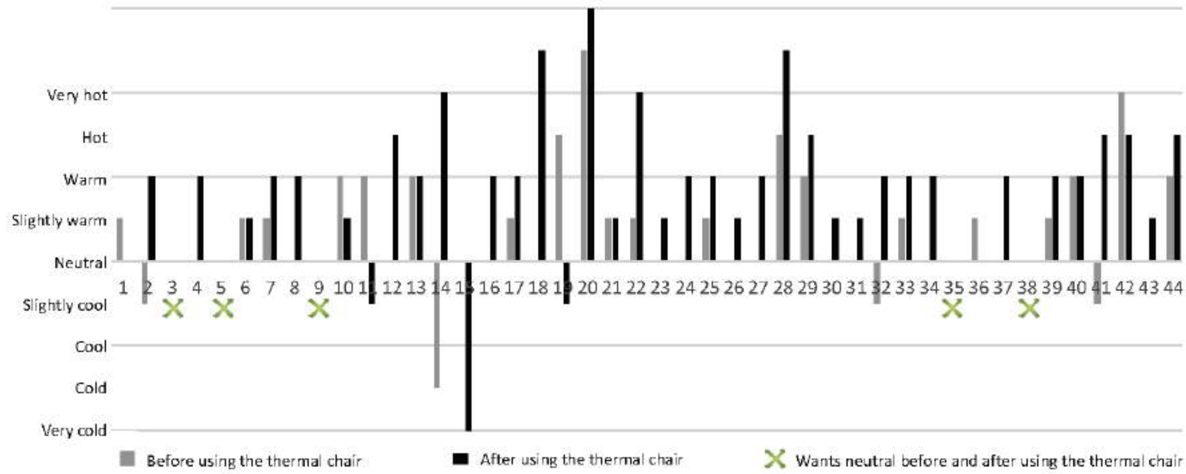


Figure 3. Thermal decision of the respondents before and after using the chair: do they want to feel neutral?

Comfort and satisfaction of the respondents before and after using the chair were examined through the seven point ASHRAE scale, as presented in Figure 4. Before using the chair, twenty six participants felt comfortable or slightly comfortable and twenty felt satisfied or very satisfied. Sixteen comfortable participants and eleven satisfied respondents did not have a neutral thermal decision. Six respondent with a neutral thermal sensation felt slightly uncomfortable to slightly comfortable. Nine respondents with a neutral thermal sensation and eleven participants with a neutral thermal decision felt dissatisfied to slightly satisfied. After using the thermal chair, the number of comfortable respondents reached to thirty four, which is 18% higher than before using chair. The satisfaction of the users reached to 80%, which is 34% improvement. After using the chair, 94% of the comfortable respondents and 88% of the satisfied participants had a thermal decision other than neutral (slightly warm to very hot).

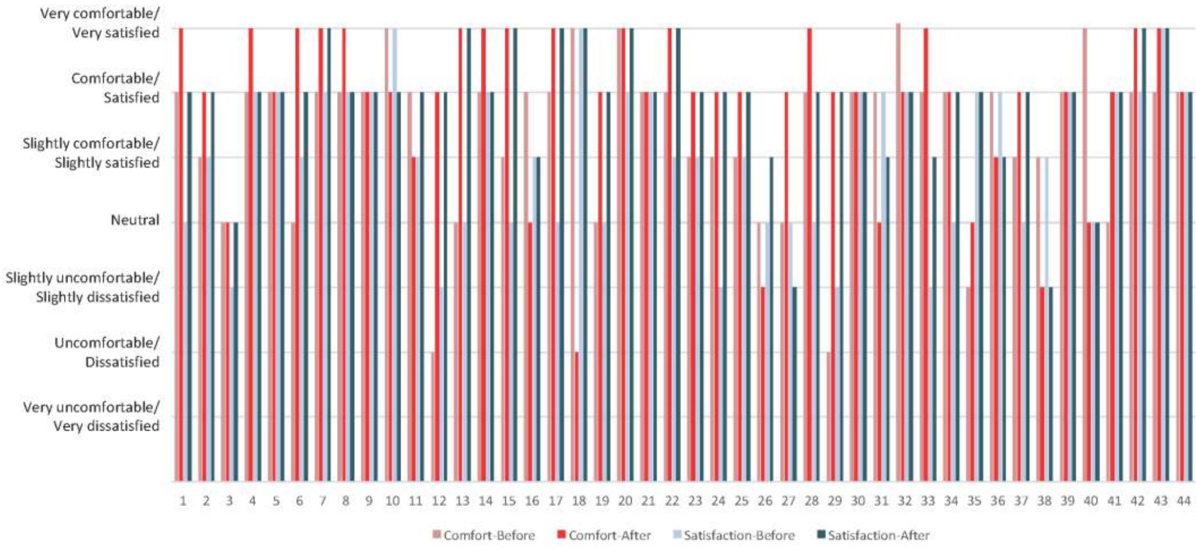


Figure 4. Comfort and satisfaction of the participants before and after using the chair

Figure 5 demonstrates the preference of the users in warming and cooling different body parts. It suggests that over 80% of the users prefer to warm their back, while over 50% of them prefer to warm their seat, feet and legs. 44.7% of the users preferred heating for their hands, but 54.1% of them preferred no heating or cooling for their faces. Overall, over half of the users prefer to heat individual body parts, with back and feet being more in demand of heating, while there is limited preference to heat or cool the face.

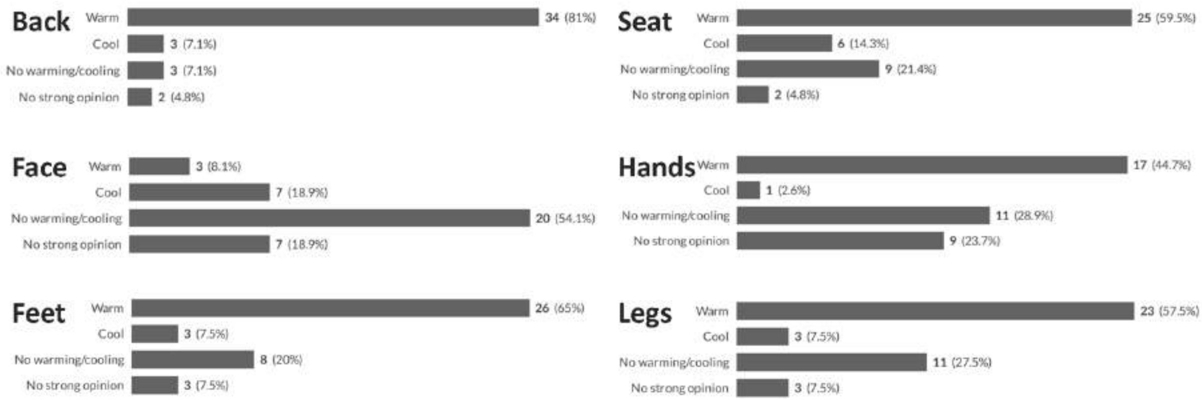


Figure 5. User's preference to warm/cool different body parts

Based on field test measurement, the current energy cost of running the thermal chair eight hours a day (working hours) is up to 5p a day when both seat and back or set on the maximum temperature. 80% of the respondents found this energy cost as reasonable or very reasonable.

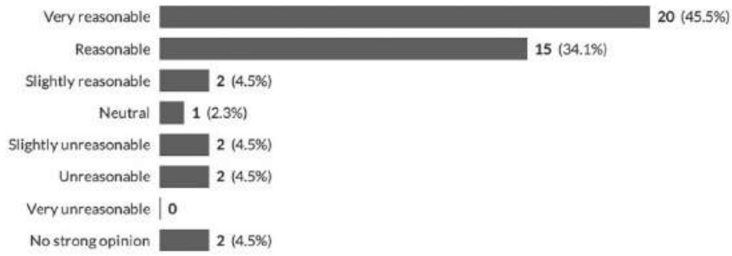


Figure 6. Users' views on the energy costing of the chair (up to 5 pence a day when running 8 hours on maximum heating)

Figure 7 shows the thermal sensation of the users' back before and after using the thermal chair. It indicates that the thermal sensation of only four occupants remained the same. Also, only nine users had a neutral thermal sensation after using the chair, suggesting that only nine users set the temperature of the back of the seat so that they feel neutral. Overall, only six respondents, who set the temperature of the back to feel neutral, had a thermal sensation other than neutral before using the chair. Fourteen respondents felt neutral around their back before using the thermal chair; however, after using the chair, they had a thermal sensation other than neutral. This suggests that these respondents set the temperature of the back of the thermal chair so that they feel other than neutral. In seven of these fourteen cases the recorded thermal sensation was warm. In thirty cases, the respondent deliberately set the back temperature to feel slightly warm to hot, while previously they felt less warm. Twenty three respondents, who had a change in their thermal sensation resulting feeling other than neutral, reported to have higher comfort or satisfaction levels. This suggests that having a thermal sensation other than neutral at their back made them more comfortable or satisfied.

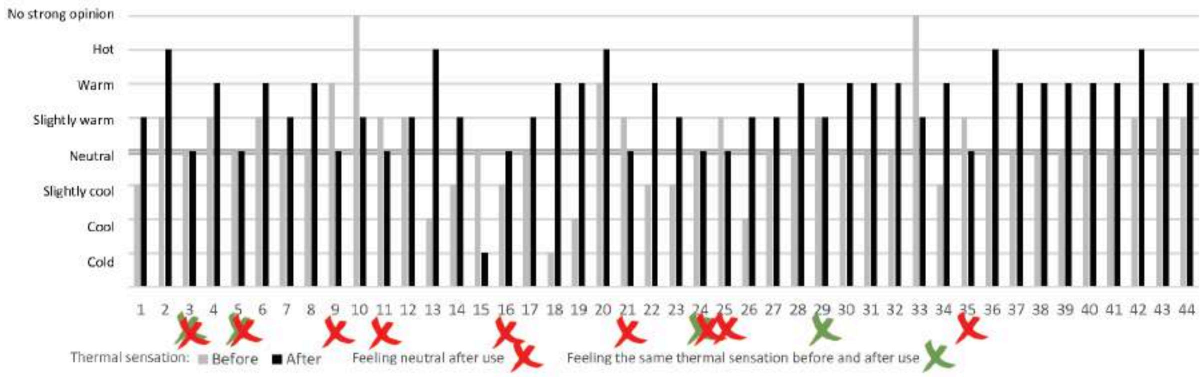


Figure 7. Back: thermal sensation of the back of the users before and after using the thermal chair

Figure 8 demonstrates the thermal sensation of the users' seat before and after using the chair. It indicates that the thermal sensation of only six occupants remained the same. Also, only nine users had a neutral thermal sensation after using the chair, suggesting that only nine users set the temperature of the back of the seat so that they feel neutral. Overall, only five respondents, who set the temperature of the seat to feel neutral, had a thermal sensation other than neutral before using the chair. Sixteen respondents felt neutral around their seat before using the thermal chair; however, after using the chair, thirteen of them had a thermal sensation other than neutral. This suggests that these thirteen respondents set the temperature of the seat of the thermal chair so that they feel other than neutral (between slightly warm to hot). In twenty five cases, the respondent deliberately set the seat temperature to feel slightly warm to hot, while previously they felt less warm. Twenty one respondents, who had a change in their thermal sensation resulting feeling other than neutral, reported to have higher comfort or satisfaction levels. This suggests that having a thermal sensation other than neutral at their seat made them more comfortable or satisfied. Comparing the results to Figure 7 shows that overall, only five individuals wanted to feel neutral on both their back and their seat after using the chair. Only eight individuals set the temperature settings of the chair so that they feel neutral at their back or their seat.

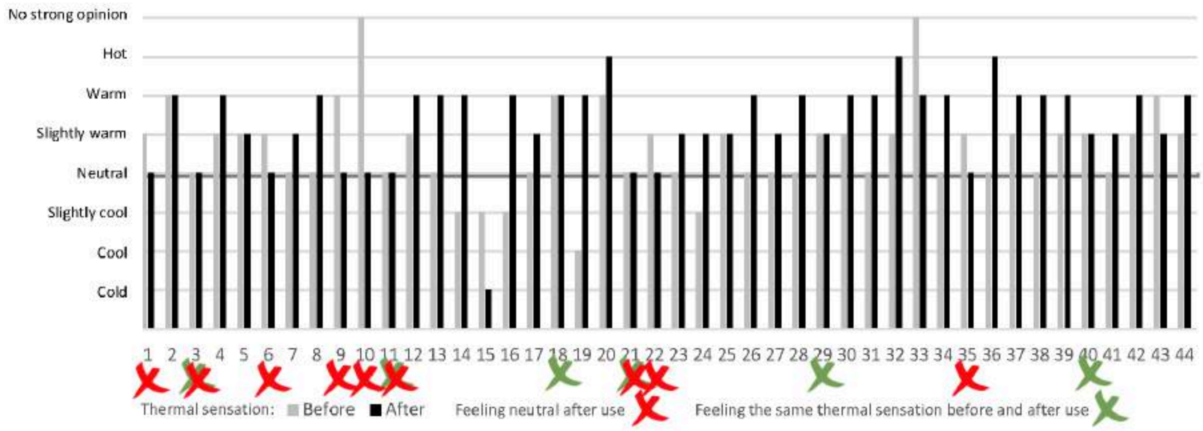


Figure 8. Seat: thermal sensation of the seat of the users before and after using the thermal chair

The results of the field study regarding the thermal sensation of the users when changing the thermal settings of the backrest and seat of the chair were align with the results of the CFD analysis. However, the CFD analysis predicted thermal discomfort of the user as higher temperature settings were used on the chair, while the field test shows higher user comfort and satisfaction. It indicates that some respondents deliberately left the thermal settings on high temperatures suggesting they wanted to feel warm or hot. This shows the current limitations of computer simulation based on PMV model, as the dynamic aspect of thermal comfort is not considered and thermoneutrality is the measure of thermal comfort. Thus, this study recommends new approaches, such as the work of Kim et al (2018), in which the computer system analyses the changes in user requirement in more depth rather than relying simply on the number of participants in a limited study.

5. Discussion and Conclusion

Overall, the results indicated that thermal decision of the occupants is dynamic and it is subject to change, suggesting a fixed and inflexible thermal environment is less likely to provide thermal comfort and satisfaction. In only nine cases (i.e. 20%) the thermal decision of the respondent remained the same before and after using the thermal chair. In most cases, the occupant's decision was significantly different before and after using the thermal chair (e.g. from neutral to warm), while there was an improvement comfort (18%) and satisfaction (34%). Furthermore, a neutral thermal sensation does not necessarily indicate thermal comfort of the occupant, as 89% of the respondents wanted to feel sensations other than neutral at some point during the study. The results indicated that localised thermal comfort increased overall thermal comfort of the occupant. Respondents expressed their satisfaction of localised thermal control and their willingness to pay for the potential energy costs. Over 80% of the users preferred to warm their back and over 50% of them preferred to warm their seat, feet and legs. The desire to warm the hands was less (44%), while there was limited preference for facial warming. Over half of the respondents deliberately set the back and seat temperatures of the chair so that they feel slightly warm to warm. Nearly half of the respondents, who had a change in their thermal sensation resulting feeling other than neutral in their back or seat, reported to have higher comfort or satisfaction levels. This suggests that having a thermal sensation other than neutral at their back or seat made them more comfortable or satisfied. 72% of the participants, who experienced a thermal sensation other than neutral before or after using the chair stated to feel comfortable and 65% expressed their satisfaction. This finding is in line with the findings of Shahzad et al (2018), Shahzad (2014) and Humphreys and Hancock (2007) indicating that a neutral thermal sensation does not guarantee thermal comfort. The dynamic aspect of thermal comfort is an important factor, which influences the design of the thermal environment. This study suggests the application of localised personal control of the thermal environment in order to provide thermal comfort. In this way, the occupant can find their own comfort at any given time according to their immediate and dynamic requirements. The numerical modelling of the thermal performance of the thermal chair with heated seat and backrest was conducted using the commercial Computational Fluid Dynamics (CFD) tool FLUENT17. The 3D steady Reynolds-averaged Navier–Stokes equations were solved in combination with the k-ε turbulence model. The effect of varying the seat and back rest temperature settings (low, medium and high) on Predicted Mean Vote (PMV) at different locations were investigated. The study recommends the need for improvement in computer simulations to incorporate the dynamic aspect of thermal comfort and consideration of various thermal sensations and the thermal decision of the user as comfort status.

6. References

ASHRAE, A.S., 2013. Standard 55-2013. Thermal environmental conditions for human occupancy, p.12.

Brengelmann, G.L. and Savage, M.V., (1997). Temperature regulation in the neutral zone. New York Academy of Sciences, 813(1), pp.39-50.

Cigler, J., Privara, S., Vana, Z., Zacekova, E. & Ferkl, L. 2012. Optimization of Predicted Mean Vote Index within Model Predictive Control Framework: Computationally Tractable Solution. Energy and Building, 52, 39-49.
de Dear, R. 1994. Outdoor Climatic Influences on Indoor Thermal Comfort Requirements. In: OSELAND, N. A. & HUMPHREYS, M. A. (eds.) Thermal Comfort: Past, Present and Future. Watford: Building Research Establishment.
Deng, Q., Wang, R., Li, Y., Miao, Y. and Zhao, J., 2017. Human thermal sensation and comfort in a non-uniform environment with personalized heating. Science of The Total Environment, 578, pp.242-248.
Fanger, P.O., 1970. Thermal comfort. Analysis and applications in environmental engineering. Thermal comfort. Analysis and applications in environmental engineering
Fojtlín, M., Fišer, J., Pokorný, J., Povalač, A., Urbanec, T. and Jícha, M., 2017. An innovative HVAC control system: Implementation and testing in a vehicular cabin. Journal of thermal biology, 70, pp.64-68.
Handbook AS. ASHRAE handbook–fundamentals. Atlanta, GA. 2009.
Hawkes, D. The Selective Environment; An approach to environmentally responsive architecture, London, Spon Press. 2002.
Humphreys MA, Hancock M. Do people like to feel 'neutral'?: Exploring the variation of the desired thermal sensation on the ASHRAE scale. Energy and Buildings. 2007 Jul 31;39(7):867-74.
Ioannou, A. and Itard, L., 2017. In-situ and real time measurements of thermal comfort and its determinants in thirty residential dwellings in the Netherlands. Energy and Buildings, 139, pp.487-505
Kim, J., Schiavon, S. and Brager, G., 2018. Personal comfort models–A new paradigm in thermal comfort for occupant-centric environmental control. Building and Environment.
Kogawa, Y., Nobe, T. and Onga, A., 2007. Practical investigation of cool chair in warm offices. Proceedings of Clima'07.
Kontes, G.D., Giannakis, G.I., Horn, P., Steiger, S. and Rovas, D.V., 2017. Using thermostats for indoor climate control in office buildings: The effect on thermal comfort. Energies, 10(9), p.1368.
Kwong QJ, Adam NM, Sahari BB. Thermal comfort assessment and potential for energy efficiency enhancement in modern tropical buildings: A review. Energy and Buildings. 2014 Jan 31;68:547-57.
Liu, J., Yao, R., Wang, J. & Li, B. 2012. Occupants' Behavioural Adaptation in Workplaces with Non-Central Heating and Cooling Systems. Applied Thermal Engineering, 35, 40-54.
Mao, N., Pan, D., Li, Z., Xu, Y., Song, M. and Deng, S., 2017. A numerical study on influences of building envelope heat gain on operating performances of a bed-based task/ambient air conditioning (TAC) system in energy saving and thermal comfort. Applied Energy, 192, pp.213-221.
McCartney KJ, Nicol JF. Developing an adaptive control algorithm for Europe. Energy and buildings. 2002 Jul 31;34(6):623-35.
Nicol, J. F. & Humphreys, M. A. 1973. Thermal comfort as part of a self-regulating system. Builiding Research & Information, 1, 174-179.
Parkhurst, G., Parnaby, R. 2008. Growth in Mobile Air-Conditioning. BRI-36.
Schellen, L., Loonans, M., DE Wit, M. & Van Marken Lightenbelt, W. 2013. The Influence of Different Cooling Techniques and Gender on Thermal Perception. Building Research and Information, 41, 330-341.
Shahzad S. Individual thermal control in the workplace: cellular vs open plan offices: Norwegian and British case studies. 2014. University of Edinburgh.
Shahzad, S., Brennan, J., Theodossopoulos, D., Hughes, B. and Calautit, J.K., 2017. Energy and comfort in contemporary open plan and traditional personal offices. Applied Energy, 185, pp.1542-1555.
Shahzad, S., Calautit, J.K., Aquino, A.I., Nasir, D.S. and Hughes, B.R., 2017. A user-controlled thermal chair for an open plan workplace: CFD and field studies of thermal comfort performance. Applied Energy
Shahzad, S., Brennan, J., Theodossopoulos, D., Calautit, J.K. and Hughes, B.R., 2018. Does a neutral thermal sensation determine thermal comfort?. Building Services Engineering Research and Technology.
Takasu, M., Ooka, R., Rijal, H.B., Indraganti, M. and Singh, M.K., 2017. Study on adaptive thermal comfort in Japanese offices under various operation modes. Building and Environment, 118, pp.273-288
Van Hoof, J., 2008. Forty years of Fanger's model of thermal comfort: comfort for all?. Indoor air, 18(3), pp.182-201.
Van Marken Lightenbelt, W. and Kingma, B. R. 2013. Building and Occupant Energetics. Architectural Science Review, 56, 48-53.
Voelcker A. 2002. The selective environment-An approach to environmentally responsive architecture.
Zhang H, Arens E, Pasut W. Air temperature thresholds for indoor comfort and perceived air quality. Build Res Inf. 2011 Apr 1;39(2):134-44.
Zhang YF, Wyon DP, Fang L, Melikov AK. 2007. The influence of heated or cooled seats. Ergonomics, 50:586-600.
Zhao, P., Peffer, T., Narayanamurthy, R., Fierro, G., Raftery, P., Kaam, S. and Kim, J., 2016. Getting into the zone: how the internet of things can improve energy efficiency and demand response in a commercial building.
Watanabe, S., Shimomura, T. and Miyazaki, H., 2009. Thermal evaluation of a chair with fans as an individually controlled system. Building and Environment, 44(7), pp.1392-1398.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

'Intelligent furniture': the potential for heated armchairs to deliver thermal comfort with energy savings in the UK residential context

Shiyu Pan[1], Ziqiao Li[1]*, Dennis Loveday[1] and Peter Demian[1]

[1] School of Architecture, Building & Civil Engineering, Loughborough University, Loughborough, Leics., LE11 3TU, UK
* Correspondence email: Z.li2@lboro.ac.uk

Abstract Personal heating (or cooling) has long been considered a means for reducing energy demand and providing thermal comfort, most commonly in the form of heated seats. In this paper, findings are reported of what may be the first investigation of the potential for heated furniture to maintain occupant thermal comfort in the UK residential context. In a thermally-controlled environmental room, a thermal manikin was seated in a living-room armchair equipped with an electrically-heated blanket. Results suggested that the manikin total heat flux recorded for the PMV range -0.5 to +0.5 without heated blanket could be achieved in a room 0.7°C cooler but with the blanket operating as compensation. Chest/back radiant asymmetry across the body, and surface contact temperatures of the blanket, were both found to be well-within acceptable limits. The implication for residential energy usage was analytically simulated using an apartment ('flat') as a case study. This showed that energy-saving potential was dependant on the building's thermal performance, the building's dimensions and occupant behaviours. When extrapolated to the UK housing stock it was found that around 5.6 TWh of energy might be saved by using heated armchairs in the UK instead of whole house heating systems. 'Intelligent furniture', in the form of heated armchairs, can potentially contribute to energy saving in the UK residential context, and further investigation is warranted.

Keywords: Thermal comfort; Personal heating; Dwelling; Thermal manikin; Building energy modelling

1. Introduction

To help mitigate climate change, the UK has committed to an 80% reduction in national greenhouse gas emissions by the year 2050, compared to the 1990 baseline (HM Government, 2008). Energy use by buildings represents 40% of the total UK energy consumption (DECC, 2014). According to the Digest of UK Energy Statistics (DUKES, 2011), energy consumption by the residential sector accounted for 30.5% of final energy consumption in 2010, second only to the transport sector (35%). Meanwhile, DBEIS (2016) reports that in 2015 the residential sector consumed 29% of UK final energy consumption, with 80% of household energy being used for space and water heating.

Personal heating (or cooling) has long been considered a means for reducing the energy demand required for providing thermal comfort in the context of buildings and automotive environments. Arens et al (1998) reported that floor fans generating airspeeds of 1.4 m/s were able to extend the upper limit of acceptable temperature to 31°C at a typical office activity level (1.0 met). This finding has been supported by Zhai et al (2013) who observed that at the thermal condition of 30°C, 60% RH was acceptable with the use of floor fans in a study employing a climate chamber representing an office setting. Zhang et al (2010) set up office workstations with task-ambient conditioning systems in a chamber-based investigation, and found that the comfortable condition was maintained at temperatures ranging from 18°C to 30°C, with corresponding energy saving potential of up to 40%. Better perceived air quality will also be provided by personal cooling devices (Kaczmarczyk et al, 2004). Personal conditioning chairs that provide direct heating or cooling to local body parts, normally the back, pelvis and thighs, are widely investigated in both research and practice, especially in automotive environments. Brooks et al (1999) investigated the possibility of using heated automobile seats to improve thermal comfort in vehicle environments, which indicated that heated seats could effectively eliminate cold thermal sensation and improve thermal comfort in cool conditions. Similarly, Oi et al (2011) reported that heated seats in the vehicle cabin with operative temperatures of 10 or 20°C were able to offset the "neutral" temperature by 3°C and potentially reduce energy consumption in automobiles.

For building applications, Veselý et al (2017) compared the effects of three types of heaters (heated chair, heated desk mat and heated floor mat) on thermal comfort in a test chamber representing an office setting, and found that a heated chair was the most effective in improving thermal comfort and saving energy. Pasut et al (2015) converted a typical office chair into a heated/cooled chair by embedding fans and heating elements, to provide local heating/cooling. His chamber-based investigation demonstrated an extended acceptable temperature range from 18°C to 29°C. To evaluate the applicability of thermal chairs in the field, Shahzad et al (2017) conducted a study testing the performance of thermal chairs in an open-plan office. The results indicated that such a thermal chair was able to improve thermal comfort and satisfaction of office workers by 20% and 35%, respectively, compared to standard office chairs. Apart from applications in office buildings, Limpens-Neilen (2006) investigated the applicability of heated benches in churches, and found that the air temperature near to seated occupants was increased by 4°C to 10°C and thermal comfort was improved, though this has limited capability to heat the entire space of churches.

There have been few, if any, studies of the use of personal heating/cooling in UK dwellings, and this study may be the first investigation of the potential for 'intelligent' furniture, in the form of heated armchairs, to maintain thermal comfort for sedentary occupants in the UK residential context. The investigation reported in this paper comprises three parts. Firstly, an experimental study was conducted aimed at examining the extent to which localised armchair heating can maintain sedentary whole-body thermal comfort whilst room operative temperatures are lowered, tested using a thermal manikin in a well-controlled environmental chamber. Secondly, the wider aspects of implementing heated armchairs will be considered, in terms of comfort criteria, general health issues and practical application in the UK's residential context. Finally, the estimated potential energy benefits and limitations will be discussed.

2. Methodology

The use of thermal manikins to evaluate thermal environments has been adopted in many studies. Generally, thermal manikins indicate the total heat loss from the manikin's surfaces in particular environmental conditions, and this is typically transformed into an equivalent temperature (ET*). For example, a dry thermal manikin "VOLTMAN" was used in defining the human requirements envelope in vehicle environments by measuring the manikin's total heat loss (Wyon et al, 1989). Nilsson et al (1997) compared the experimental results from a manikin with subjective votes, and found high correlations for each body segment between the heat flux of manikin and mean thermal sensation of subjects and between equivalent temperature and mean thermal sensation of subjects. Watanabe et al (2010) investigated the heating/cooling effects of individually-controlled systems and successfully revealed its heating/cooling capacity using a 23-segment thermal manikin to measure heat loss under various thermal conditions. This, together with the preceding literature reported, underpinned the approach adopted for the design of the experimental work reported here. It is recognised that the PMV model is applicable to whole body thermal sensations under steady-state conditions, and may not be best-suited to the complexities of non-uniform conditions (Schellen et al, 2013) and the resulting human thermal sensations (Oi et al, 2012) as generated by localised heating. Furthermore, Tanabe (1994) suggested that using equivalent temperature (teq) based on the heat loss of a thermal manikin could be an accurate method to calculate PMV in non-uniform environments. However, since our study is a first approximation at establishing the magnitude of room operative temperature reduction, the original PMV calculation method was adopted.

This experiment was conducted in a well-controlled environmental room representing a residential living room, in which the heating effect of a 'thermal armchair' (equipped with a heated blanket) was investigated using a thermal manikin, followed by a simulation-based analysis. Specifically, with the heated blanket turned 'off' or 'on', total heat flux from the manikin was recorded for a series of room temperatures (air and mean radiant temperatures maintained equal) giving room thermal conditions that generated a range of Predicted Mean Vote (PMV) values (for known values of metabolic rate and clothing thermal insulation). The extent to which room operative temperature could be lowered whilst compensating for sedentary whole-body thermal comfort through use of the thermal armchair was then determined. For the reduced value of room operative temperature combined with operation of the heated armchair, an energy-saving analysis was carried out in the UK's housing context, using the simulation software 'Design Builder'.

2.1. Description of Environmental Room

The environmental room is located in the Sir Frank Gibb Laboratory at Loughborough University. The room is 5.4 m long, 3.05 m wide and 2.35 m high. The indoor climate condition is controlled by convective conditioning supplied by a tempered ventilation system, and radiative conditioning is provided by tempered water flowing in pipes within the four bounding walls, as shown in Figure 1. The temperatures of air supply and of each wall surface can be individually controlled.

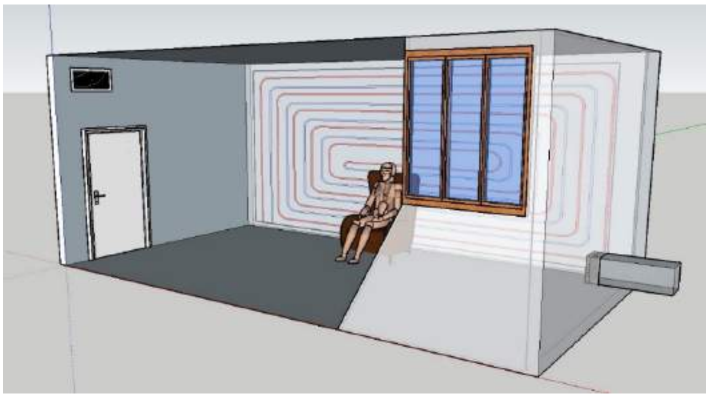


Figure 1 Schematic illustration of the environmental room, showing locations of door, window, and manikin in thermal armchair

The velocity of supply air can be controlled via a central control system which is able to effectively supply air flow in a range from 34 l/s to 75 l/s. The room has a door to the general laboratory space, as well as a multi-layer window facing the outdoor environment, and can achieve indoor temperatures within the range approximately 14-30^{o}C.

2.2. Thermal Manikin

"Victoria" is a female-form thermal manikin used in this experiment, with 20 independently-controlled segments, as shown in Figure 2. The manikin was placed in the centre of the room close to the northern wall, seated in a standard living room armchair upon a heated blanket that covered the back and seat areas of the chair. Heat flux from the manikin (total and segmental) were recorded with an estimated uncertainty of ± 1 Watt, and these values were used comparatively to assess the effect of the presence or absence of heat from the armchair on likely whole-body thermal sensations under a range of room thermal conditions.

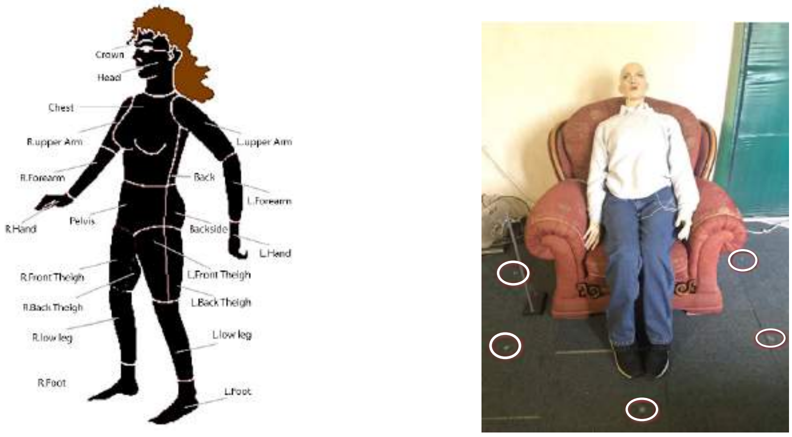


Figure 2 The thermal manikin, illustrating controllable segments (left) and seated in the armchair, wearing typical residential clothing (right)

Since the mean human skin temperature remains at approximately 34°C at thermally neutral conditions (Huizenga et al, 2004), the surface temperature of the thermal manikin was set to 34 °C to simulate the heat flux scenarios of an actual near-neutral thermal environment. The dynamic heat flux and surface temperature of each body segment were recorded at one-minute intervals via a data logger. To assess the effect of the thermal armchair in a residential setting, the thermal manikin was dressed in an ensemble typical of UK residences during winter periods. The ensemble is described in Table 1, and had a total insulation value of 0.93 clo. To this was added an additional 0.15 clo to account for the thermal insulation provided by the armchair

Table 1 Description of clothing ensemble and insulation

Garment description	Insulation value (clo)
Long-sleeved shirt	0.25
Long-sleeved sweatshirt	0.34
Straight trousers (thin)	0.15
Ankle-length athletic socks	0.02
Thin-soled shoes	0.02
Executive chair = 'armchair'	0.15

2.3. Experimental Equipment

(1) Heating Blanket

The electrically-operated heating blanket (Figure 3) was 1.25 m long and 0.6 m wide, and was placed flat upon the sitting and backrest areas of the armchair. This provided heating directly to the back, rear pelvic and back-of-thigh regions of the thermal manikin. The blanket had three heating settings, but to ensure that the heat flow throughout all experiments remained in the direction from manikin to blanket (necessary for correct manikin operation), only the first heating level was employed, which provided a blanket surface temperature of approximately 31.5°C and a blanket measured heat emission of 10.5 Watts.

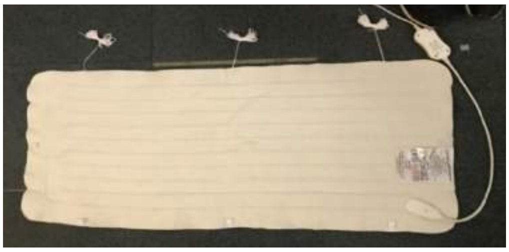


Figure 3 The experimental heating blanket

(2) Measurement Devices

The four environmental parameters: air temperature, mean radiant temperature, relative humidity and air velocity (Fanger, 1970) were continuously recorded. Specifically, during the experiment, relative humidity and air temperature were measured in front of the manikin using a HOBO MX1101 every 15 seconds. The mean radiant temperature was logged every 15 seconds in the centre of the room. Air velocity was measured with an anemometer placed near the manikin at the knee height. The type and levels of uncertainty of each equipment are listed in Table 2.

Table 2 The type and levels of uncertainty of the measuring equipment

Environmental factor	Equipment type	Accuracy
Air temperature	HOBO MX1101	± 0.2 °C
Mean radiant temperature	HOBO UX100-014M	± 0.6 °C
Relative humidity	HOBO MX1101	± 2%
Air speed	Testo 425	±0.03 m/s

2.4. Experimental Procedure

Before beginning the experiment, air velocity and air temperature were measured in the space around manikin at five points illustrated in Figure 2 (white circles) and at heights of 0.1m, 0.6m and 1.1m above the floor. This ensured that the operating manikin was in a thermally stable environment (air speed less than 0.1m/s and air temperature stable) in the experiment. A total of 14 test cases were generated, each corresponding to a different environmental condition (Table 3) across the (air and mean radiant) temperature range 16.3 – 27.4 ^{o}C. Each environmental condition was tested twice - with or without - the heating blanket operating. The environmental conditions were designed to achieve a certain PMV (predicted mean vote) value for situations without the operation of the heating blanket. To do this, it was assumed that activity level remained at 1 met to simulate the metabolic rate of a sedentary occupant in their living room, with insulation of 0.93 clo (see section 2.2). As a result, the corresponding PMV ranged from +1.0 to -2.0, indicating whole-body thermal sensations ranging from 'slightly warm' to 'cool'.

Table 3 the experiment conditions

Environmental condition	Air temp (equal to) mean radiant temp (°C)	Relative humidity (%)	Air speed (m/s)	Activity level (met)	Clo value (Clo)	PMV
Condition 1	16.3	64	0.04	1.0	0.93	-2
Condition 2	18.2	55	0.04	1.0	0.93	-1.5
Condition 3	20.0	52	0.04	1.0	0.93	- 1
Condition 4	21.8	47	0.04	1.0	0.93	-0.5
Condition 5	23.7	44	0.04	1.0	0.93	0
Condition 6	25.5	39	0.04	1.0	0.93	+ 0.5
Condition 7	27.4	36	0.04	1.0	0.93	+ 1.0

For each case, whole-body heat flux from the manikin was recorded at steady state conditions, with and without the operation of the heating blanket. Figure 4 illustrates the procedure. To avoid additional heat gains, experimenters remained outside the environmental room during tests.

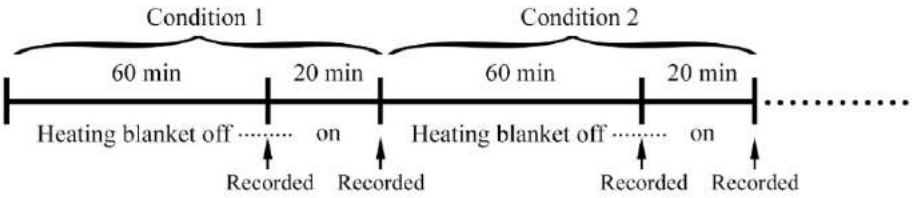


Figure 4 The schematic procedure of experiment

3. Experiment Results

The heat losses through the surfaces of the thermal manikin were compared in the aspects of environmental conditions and heating blanket operations. For the situations without heating blanket operation, and for all the environmental conditions tested, Figure 6 summarises the averaged whole-body heat loss of the thermal manikin as a function of PMV values ranging from -2 to +1.

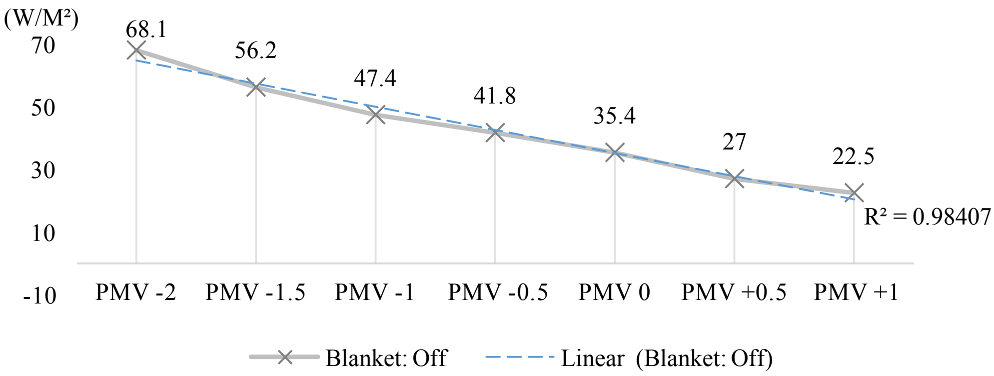


Figure 6 Whole-body heat loss of the manikin versus PMV (heating blanket off). (Manikin heat flux uncertainty estimated as ± 1 Watt).

A highly linear relationship (R^2 = 0.98) was found between manikin whole-body heat loss and PMV, with heat loss consistently decreasing as the PMV changed from 'cool' to 'slightly warm', which confirms alignment with the approach described by Gao et al (2017) and supports the statement of Nilsson et al (1997) who found that the thermal mean votes correlated to the change of the heat loss of manikins.

The above approach was used to compare the likely effect of armchair-based heating blanket usage on thermal comfort. Whole-body heat loss from the thermal manikin was compared for the two heating blanket operation modes (on/off) at the different PMV conditions, as shown in Figure 7.

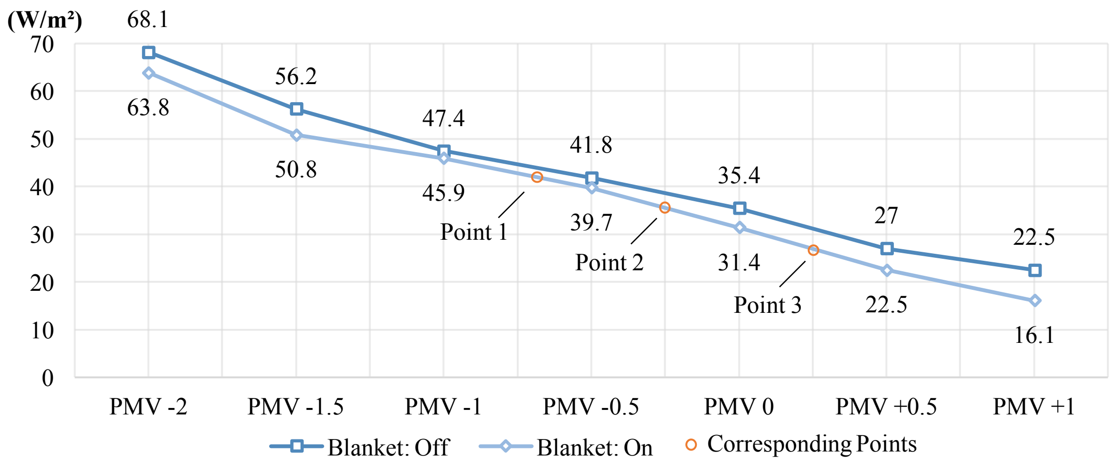


Figure 7 Manikin whole-body heat loss for blanket on or off versus PMV conditions (manikin heat flux uncertainty estimated as ± 1 Watt).

Figure 7 illustrates that operation of the heating blanket (acting as a heated armchair) reduced the whole-body heat losses from the manikin at all thermal conditions tested.

Focussing specifically on the PMV range considered acceptable for thermal comfort (PMV -0.5 to PMV +0.5), use of the heating blanket compensates for, and enables acceptability of, room thermal conditions ranging from PMVs of -0.67 to +0.26 (refer to points 1, 2 and 3 in Figure 7). These points indicate that using the heating blanket could result in preserving the same value of whole-body heat loss, but for the cooler room thermal conditions. To be specific, the previously acceptable room thermal conditions with PMV values at -0.5, 0 and +0.5 could be shifted to the new room thermal conditions with PMV values at -0.67, -0.24 and +0.26 (point 1, 2 and 3), respectively. For the situations tested, these correspond to a reduction in room temperature of 0.7°C, as demonstrated in Table 4.

Table 4 The changes of acceptable ambient temperature in conjunction with the heating blanket

Acceptable thermal conditions (Blanket Off)	Acceptable thermal conditions (Blanket On)	Ambient Temp (Blanket Off)	Ambient Temp (Blanket On)	Temperature difference
PMV +0.5	PMV +0.26	25.4 °C	24.7 °C	0.7 °C
PMV 0	PMV -0.24	23.7 °C	23.0 °C	0.7 °C
PMV -0.5	PMV -0.67	21.7 °C	21.0 °C	0.7 °C

Were this to remain fully applicable in the living areas of dwellings, then the usage of heated (‘intelligent’) armchairs might allow a reduction of 0.7 °C in indoor room ambient temperatures without adversely influencing the overall thermal sensation of seated occupants under steady state conditions and wearing similar clothing to that tested. The potential effects of this in terms of energy savings are discussed in the next section.

4. Analysis and Discussion in the UK residential context

According to English Housing Survey (DCLG, 2017), in England, there were approximately 23.5 million residential buildings in 2015. Based on English Housing Survey, typical dwelling types in the UK can be grouped into 10 categories while the usable floor area of UK dwellings can be grouped into 5 categories, as demonstrated in Table 5. Among these building types, the proportion of apartments (commonly termed ‘flats’ in the UK) was approximately 42% of total dwellings in England in 2015 (DCLG, 2017). Therefore, a flat was used as a simulation model in this study due to its universality.

Table 5 Typical dwelling types, insulation performance and usable floor area of dwellings in the UK

Dwelling types	Limiting U-value of previous regulation (W/m2 K)					Usable floor area
	Year	Wall	Windows	Roof	Floor	
Terraced house; Semi-detached house; Detached house; Bungalow; Flat	1976	1.0	n/a	0.6	n/a	
	1982	0.6	n/a	0.35	n/a	Less than 50m^2
	1990	0.54	3.3	0.25	0.45	50 to 69 m^2
	1995	0.45	3.3	0.25	0.35	70 to 89 m^2
	2000	0.35	2.2	0.25	0.25	90 to 109 m^2
	2006	0.35	2.1	0.2	0.25	110 m^2 or more
	2010	0.3	2	0.2	0.25	

The first building regulation for U-value of building envelopes in England was established in 1976 (Killip, 2005), while Dowson et al (2012) summarised the historic U-value of thermal envelope in each building regulation since 1976, as shown in Table 5. However, according to English Housing Survey (DCLG, 2017), until 2015, nearly half of the existing domestic stocks were built before 1964, and only 49.1% and 81.4% of dwellings were installed with wall insulation and full double glazing, respectively.

Meanwhile, Steemers et al (2009) and Firth et al (2010) reported the average number of occupants in households was 2.52 people and 2.65 people, respectively.

Considering the energy-saving performance of the heated armchair would be affected by heating loads in homes, this simulation would focus on the influencing variables on heating loads, such as thermal performance of building envelopes, the dimension of buildings, the glazing ratio and the number of occupants. Meanwhile, the operation time of heated armchairs would be simulated as another variable.

According to DECC (2014), the heating season in the UK generally lasts for 5.6 months, which starts from October and extends to April the following year. SAP (2012) suggests the demand temperature in the living areas of dwellings is 21°C, while the whole house needs to be heated for 9 hours a day on weekdays and 16 hours a day on weekends. Martínez-González et al (1999) investigated the average seating time, including all seated leisure activities, of male and female adults at home per week in the European countries, and found on average that males spent 24.6 hours per week sitting at home whilst females spent 23.2 hours seated.

Additionally, although a dynamic ventilation rate depending on the number of occupants is required in new-built dwellings by Part F of the Building Regulations (Regulations, 2010), the main approach of obtaining fresh air in the majority of dwellings in the UK relies on air infiltration through the building fabric. Pan (2010) summarised the typical air permeability of dwellings in UK's building regulations ranges from 10 m^3/(h m^2) to 1 m^3/(h m^2) at 50 Pa, while Grigg et al (2004) revealed the average air permeability of new-built dwellings in 2002 was about 9 m^3/(h m^2) at 50 Pa. Hence, in this simulation, the ventilation rate is determined by 5 m^3/(h m^2) at 50 Pa of air permeability which is also recommended by SAP (2012).

Based on the information summarised above, several energy simulations have been conducted using DesignBuilder to determine the energy-saving potentials of thermal furniture in the UK dwellings. In the simulation, weather data at the location of London Gatwick Airport was selected in this simulation. The heating is assumed to heat the whole building in the heating seasons (October – April), while the heating operation periods required is presumed to be 9 hours and 16 hours for weekdays and weekends, respectively. The operation period of heated armchairs depends on the assumption in the simulation, but is considered to be up to 77 hours per week, as specified in Table 6.

Based on the experiment result, the use of heated armchairs is able to compensate 0.7°C of indoor ambient temperature. Therefore, it is assumed the ambient temperature in homes will be reduced from 23.7°C to 23.0°C in heating seasons when hated armchairs are in operation.

The simulation scenarios are shown in Table 6. There are 5 variables factors and totally 20 scenarios. For each scenario, except for the values specified in the table, the rest of values are the same as those in the baseline. Each scenario would be simulated twice in cases with and without heated armchairs.

4.1. Energy-saving Potential

The energy saving potential, here, is defined as the difference between the energy consumption in the condition of operative temperature of 23.7°C (PMV = 0, suggested in Table 4) without heated armchairs and the energy consumption in the condition of operative temperature of 23.0 °C plus the energy consumption from the heated armchair.

Importantly, it is assumed that one heated armchair is only able to serve one person, and it would be used during heating seasons (28 weeks). The power of one heating blanket is 10.5W, and the energy consumption of one heated armchair in the heating season was manually calculated by the power times operation hours, as shown in equation 1.

$$W_{annual} = N_{armchair} \times P_{armchair} \times T_{per\ week} \times T_{weeks} \qquad \ldots ①$$

Where, W_{annual} – Annual energy consumption of hated armchair (KWh);
$N_{armchair}$ – Number of heated armchairs in use;
$P_{armchair}$ – The power of each heated armchair (W);
$T_{per\ week}$ – Operation period of heated armchair per week (hours);
T_{weeks} – The period of heating season (weeks).

Table 6 The simulation scenarios

Baseline								
Scenario No.	U-value (W/m2 K)				No. of Occupants	Room Dimension (L*W*H) (m)	Glazing ratio	Operation time per week (h)[a]
	Wall	Windows	Roof	Floor				
Baseline	0.3	2.0	0.2	0.25	2	9*10*3.5	30%	24[e]

Factor 1 – Thermal performance of building envelopes					
Scenario No.		1	2	3	4
U-value (W/m2 K)	Wall	2.0	1.0	0.54	0.3
	Windows	3.8	3.8	3.3	2.0
	Roof	1.0	0.6	0.25	0.2
	Floor	0.7	0.5	0.45	0.25

Factor 2 – Number of occupants using heated armchairs				
Scenario No.	5	6	7	8
Number of occupants	1	2	3	4

Factor 3 – Dimension of buildings				
Scenario No.	9	10	11	12
Room Dimension (L*W*H) (m)	5*10*3.5	7*10*3.5	9*10*3.5	11*10*3.5

Factor 4 – Glazing ratio				
Scenario No.	13	14	15	16
Glazing ratio	15%	20%	25%	30%

Factor 5 – Operation time of heated armchairs				
Scenario No.	17	18	19	20
Operation time per week (h)	11[b]	24[e]	49[c]	77[d]

Note:
a – it stands for the weekly operation time of heated armchairs; the maximum operation time for one week is 77 hours, which is calculated based on the required weekly heating period.
b – weekday: 22:00-23:00; weekends: 20:00-23:00;
c – weekday: 8:00-9:00, 19:00-23:00; weekends: 8:00-12:00, 13:00-17:00, 19:00-23:00;
d – all heating period;
e – weekdays: 21:00-23:00; weekends: 09:00-11:00; 20:00-23:00.

Based on the simulation results, the energy saving potentials of using heated armchairs in different variable cases are shown in Figure 8, and discussed as follows.

Since heating loads can be reduced by increasing thermal performance of building envelopes, the amount of energy conservation by using heated armchairs decreased with improvement of U-values of envelope components. However, the highest percentage of energy saving is observed in the best-insulated case, which indicates the thermal furniture, such as heated armchairs, could lead to additional energy savings even though buildings have been well insulated.

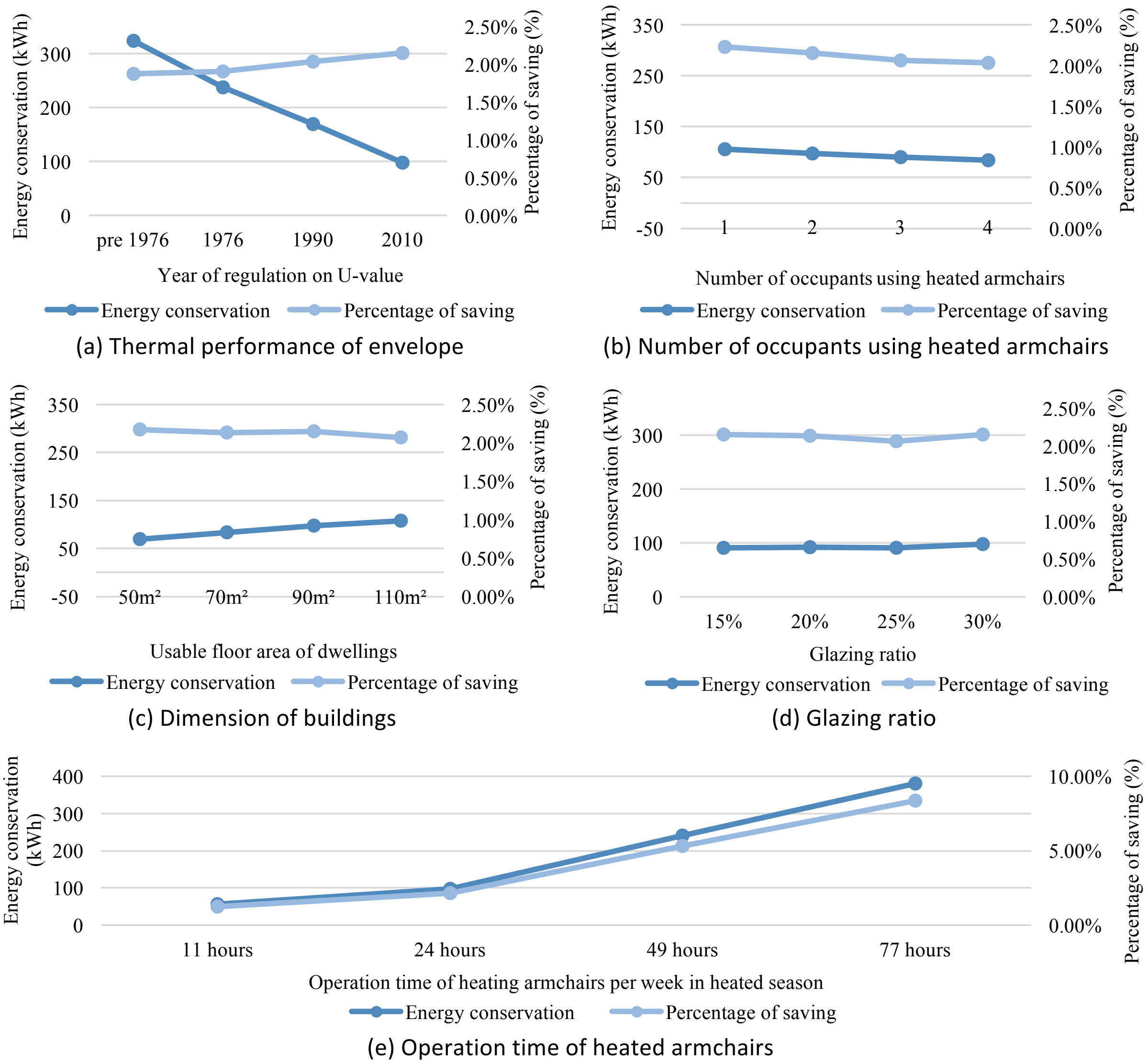


Figure 8 The energy conservation of heated armchairs in various scenarios

Based on Figure 8-b, less energy can be saved when there are more occupants using heated armchairs. The reason is total energy consumption is reduced in dwellings, as more occupants will result in more heat gains and less heating demand. Therefore, theoretically, the energy-saving potential of heated armchairs will be totally eliminated at a certain number of heated armchairs in operation, but such a large number of occupants in a single dwelling would be uncommon in the UK context.

This simulation adopted the fixed air permeability to supply sufficient fresh air. If the ventilation rate in dwellings is determined by the number of people, as suggested by Part F (Regulations 2010), more occupants may result in higher heating loads from ventilation, leading to increasing energy-saving potentials by using heated armchairs. Therefore, the usage of heated armchairs is suitable for multiple occupants in the UK, but the energy-saving effectiveness will depend on the number of occupants and the ventilation mode in dwellings.

Although there were some fluctuations, the smaller dimension of indoor space can, indeed, benefit from heated armchairs with better energy performance. For example, energy consumption could be reduced by 2% by two heated armchairs in dwellings with 50 m^2 floor area, as shown in Figure 8-c. However, dwellings with larger floor areas might potentially accommodate more occupants, so the energy saving potential may be greater in the large size dwellings in reality. Glazing ratio affecting solar heat gains shows relatively low impacts on the performance of heated armchairs. The range from 15% to 30% of glazing ratio has been found to show minor changes in either the amount or the percentage of energy saving.

Since different occupant behaviours in terms of sitting time at homes may influence the actual performance of heated armchairs, different operation scenarios have been simulated as the operational period of heated armchairs. Maximum 8% of the annual heating energy can be reduced by using heated armchairs 77 hours per week in the heating season. Even if only using heated armchairs 1 hour per weekday and 3 hours per weekend, it still can achieve about 1.24% of energy conservation.

4.2. Acceptability and Health issues

Alongside the discussions above of the potential of heated armchairs to save energy in the UK residential context, it is also important that wider aspects of thermal acceptability are considered. For the heated armchair to be considered thermally acceptable by its occupants, two conditions must be met: one is that the chair surface temperature must remain in the range considered safe and acceptable to humans (or household pets) in terms of skin contact temperature, and the other is that the temperature difference between the heated chair surface and the room ambient temperature must be within the limitation range of thermal asymmetry.

Havenith (2005) points out that the heat tolerance of people would depend on their age, gender, fitness, acclimatisation, morphology and fat, in which age and fitness are the most important factors. Wienert et al (1983) suggests that 43°C is the highest skin temperature which can be tolerated for about 8 hours with no restricted blood flow. The surface temperature of the heating blanket used in this study was 31.5°C, which is lower than the thresholds of causing physiological disorder. In terms of temperature asymmetry, assuming the condition for vertical surfaces applies (ASHRAE Standard 55, 2013), then this too remains acceptable for a chair surface temperature of 31.5°C and a room ambient temperature in the range 21-24.7°C as was the case in this study. In other studies, humidity has also been found to be a crucial factor in determining local thermal comfort of people sitting in chairs, as the water vapour released by the body's skin should be able to disperse.

As a solution, by improving the materials of seat covers, Glassford et al (1979) found that the inclusion of small holes in a seat's surface could change some unacceptable conditions into an acceptable range.

An extensive consideration of potential health issues (benefits or drawbacks) related to residential use of heated seats is beyond the scope of this paper. Such issues might relate to the long-term health effects of inhalation of air at slightly cooler temperatures than might currently prevail as a result of heated armchair use, whether there are any potential effects on male fertility (Jung et al, 2008), and whether heated chair use influences the length of time spent in sedentary mode by occupants in their homes with any consequences for health. It is recommended that all potential health-related aspects are fully investigated prior to adoption of heated 'intelligent' seating in homes.

4.3. Generalisation and Adaptation Opportunity

There were 23.5 million dwellings in the UK in 2015 (DCLG, 2017), and by 2011, approximately 280 TWh of energy was consumed by space heating in households (Palmer and Cooper, 2012). Based on the analysis above, 2% would be a reasonable percentage to be set as the energy saving potential of heated armchairs. Therefore, presumably, 5.6 TWh of energy could be saved by simply using heated armchairs in UK dwellings, though this number would depend on many factors, such as occupant behaviours, U-values of building envelope, occupant numbers and building dimensions.

The research described in this paper on heated armchairs has been conducted under steady state conditions and has employed the PMV approach for objective comparison of situations with and without the operation of the heated blanket. Adaptive opportunities have thus been assumed to be none. The findings might therefore be more applicable to domestic situations of extended sedentary periods with little or no adaptive actions. However, actual temperatures in UK homes are often lower than expected. For example, Kane et al (2011) investigated 292 dwellings in Leicester, UK and found average air temperature in living rooms was only 18.4°C during the day with a slightly higher temperature at evening (19.4°C) suggesting that adaptive opportunities play a significant role in achievement of residential thermal comfort. Thermal furniture, such as heated armchairs, may provide occupants with another thermal adaptation opportunity. In some cases, a single heated armchair in the living rooms could be able to offset the heating demand of occupants when they are not willing to increase energy bills by heating the entire home. In other cases, the heated armchair also offers a chance to satisfy the individual's thermal preference when the room temperature is neutral to others but cold to him/her. It is recommended that these aspects are investigated further.

Since the most uncomfortable local-body parts in cold conditions are the hands and feet, it may be valuable to add heating elements in the arm pads of armchairs in future designs, and/or foot-warming capability. Further, field studies involving human subjects should be conducted of actual energy performance, thermal comfort and usage acceptability of such heated armchairs in the context of dwellings.

5. Conclusions

Personal heating/cooling has long been considered a means for providing thermal comfort, leading to reducing the energy demand in the context of buildings and automotive environments. Heating/cooling chairs are one of the most common forms of personal conditioning devices. This paper reported the findings of what may be the first investigation of the potential for heated furniture to maintain occupant whole-body thermal comfort in the UK residential context. The investigation comprised laboratory work followed by thermal analysis and energy analysis. A thermal manikin was seated in an armchair, in a thermally-controlled environmental chamber operated as a standard living room, that had been equipped with an electrically-heated blanket for supplying heating to the back and rear pelvic/thigh regions.

The main findings are as follows.

- For living room thermal conditions, it was found that the manikin total heat flux recorded for the PMV range -0.5 to +0.5 without heated blanket operation could be achieved in a room 0.7°C cooler but with the blanket operating in compensation;
- Using heated armchairs in well-insulated dwellings can result in a higher proportion of energy saving than in poorly-insulated dwellings;
- The usage of heated armchairs is suitable for multiple occupants in the UK, but the energy-saving potential will depend on the number of occupants and the ventilation mode in dwellings;
- Ideally, 5.6 TWh of energy in dwellings in the UK might be saved by simply using heated armchairs, though this number would depend on many factors, such as occupancy, operation periods, U-values of building envelope, occupant numbers and building dimension; and whilst heated armchairs might offer individual dwellings a modest energy saving of only 2%, there may be other (non-energy) benefits that might lead householders to adopt this approach;
- Heated armchairs provide dwelling occupants with another thermal adaptation option, but the acceptability, health issues, energy performance and thermal comfort in real-world settings need to be fully investigated in the future, prior to adoption of this approach.

Acknowledgements

The authors gratefully acknowledge the contributions and support by laboratory technical staff in the School of Architecture, Building and Civil Engineering, Loughborough University, UK during the design and implementation of the experimental work in the School's climate chamber. Z. Li also expresses gratitude for the financial support afforded by a doctoral scholarship from Loughborough University, UK.

References

Arens, E., Xu, T., Miura, K., Hui, Z., Fountain, M., & Bauman, F. (1998). A study of occupant cooling by personally controlled air movement. Energy and buildings, 27(1), 45-59.

ASHRAE Standard. (2013). Standard 55-2013:"Thermal Environmental Conditions for Human Occupancy"; ASHRAE. Atlanta USA.

BRE, SAP. (2012). The government's standard assessment procedure for energy rating of dwellings. Building Research Establishment, Watford, UK.

Brooks, J. E., & Parsons, K. C. (1999). An ergonomics investigation into human thermal comfort using an automobile seat heated with encapsulated carbonized fabric (ECF). Ergonomics, 42(5), 661-673.

Building Regulations (2010). Approved Document F: ventilation.

DBEIS (2016). Energy Consumption in the UK. Available from: https://www.gov.uk/government/collections/energy-consumption-in-the-uk (accessed 20/11/2017).

DCLG (2017). English Housing Survey 2015 to 2016: headline report. Available from: https://www.gov.uk/government/statistics/english-housing-survey-2015-to-2016-headline-report (accessed 08/12/2017)

DECC (2014). Energy Follow-Up Survey (EFUS): 2011. Available from: https://www.gov.uk/government/statistics/energy-follow-up-survey-efus-2011 (accessed 08/12/2017)

Dowson, M., Poole, A., Harrison, D., & Susman, G. (2012). Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal. Energy Policy, 50, 294-305.

DUKES (2011) Digest of United Kingdom energy statistics. http://www.decc.gov.uk/assets/decc/11/stats/publications/dukes/2303-dukes-2011-c hapter-1-energy.pdf

Fanger, P. O. (1970). Thermal comfort. Analysis and applications in environmental engineering. Thermal comfort. Analysis and applications in environmental engineering.

Firth, S. K., Lomas, K. J., & Wright, A. J. (2010). Targeting household energy-efficiency measures using sensitivity analysis. Building Research & Information, 38(1), 25-41.

Gao, S., Li, Y., Wang, Y. A., Meng, X. Z., Zhang, L. Y., Yang, C., & Jin, L. W. (2017). A human thermal balance based evaluation of thermal comfort subject to radiant cooling system and sedentary status. *Applied Thermal Engineering*, *122*, 461-472.

Glassford, E. J., & Shvartz, E. (1979). Metabolic Heat Retention and the Vehicle Operator (No. 790289). SAE Technical Paper.

Grigg, P., & Slater, A. (2004). Assessment of energy efficiency impact of Building Regulations compliance. *A Report Prepared for the Energy Savings Trust/Energy Efficiency Partnership for Homes. Client Report*, (219683).

Havenith, G. (2005) 'Temperature regulation, Heat balance and climatic stress', in Extreme Weather Events and Public Health Responses, pp. 69–80. doi: 10.1007/3-540-28862-7_7.

HM government (2008). Climate Change Act 2008. See https://www.legislation.gov.uk/ukpga/2008/27/contents (accessed 13/11/2017).

Huizenga, C., Zhang, H., Arens, E., & Wang, D. (2004). Skin and core temperature response to partial-and whole-body heating and cooling. Journal of Thermal Biology, 29(7), 549-558.

Jung, A., Strauss, P., Lindner, H. J., & Schuppe, H. C. (2008). Influence of heating car seats on scrotal temperature. Fertility and sterility, 90(2), 335-339.

Kaczmarczyk, J., Melikov, A., & Fanger, P. O. (2004). Human response to personalized ventilation and mixing ventilation. Indoor Air, 14(s8), 17-29.

Kane, T., Firth, S. K., Lomas, K. J., Allinson, D., & Irvine, K. (2011). Variation of indoor temperatures and heating practices in UK dwellings.

Killip, G. (2005). Built Fabric & Building Regulations, Background Material F: 40% House Project, Environmental Change Institute. University of Oxford, UK.

Limpens-Neilen, D. (2006). Bench heating in monumental churches: thermal performance of a prototype. Technische Universiteit Eindhoven.

Martínez-González, M. Á., Alfredo Martinez, J., Hu, F. B., Gibney, M. J., & Kearney, J. (1999). Physical inactivity, sedentary lifestyle and obesity in the European Union. International Journal of Obesity & Related Metabolic Disorders, 23(11).

Nilsson, H., Holmer, I., Bohm, M., & Noren, O. (1997). Equivalent temperature and thermal sensation-Comparison with subjective responses. Proceedings of Comfort in the automotive industry-Recent development and achievements, 157-162.

Oi, H., Yanagi, K., Tabata, K., & Tochihara, Y. (2011). Effects of heated seat and foot heater on thermal comfort and heater energy consumption in vehicle. Ergonomics, 54(8), 690-699.

Oi, H., Tabata, K., Naka, Y., Takeda, A. and Tochihara, Y. (2012). Effects of heated seats in vehicles on thermal comfort during the initial warm-up period. Applied Ergonomics, 43, 360-367.

Palmer, J., & Cooper, I. (2012). United Kingdom housing energy fact file 2011. Department of Energy and Climate Change, London, UK, 145.

Pan, W. (2010). Relationships between air-tightness and its influencing factors of post-2006 new-build dwellings in the UK. *Building and Environment*, *45*(11), 2387-2399.

Pasut, W., Zhang, H., Arens, E., & Zhai, Y. (2015). Energy-efficient comfort with a heated/cooled chair: Results from human subject tests. Building and Environment, 84, 10-21.

Schellen, L., Loomans, M.G.L.C., Kingma, B.R.M., de Wit, M.H., Frijns, A.J.H., and van Marken Lichtenbelt, W.D. (2013). The use of a thermophysical model in the built environment to predict thermal sensation. Coupling with the indoor environment and thermal sensation. Building & Environment, 59, 10-22.

Shahzad, S., Calautit, J. K., Aquino, A. I., Nasir, D. S., & Hughes, B. R. (2017). A user-controlled thermal chair for an open plan workplace: CFD and field studies of thermal comfort performance. Applied Energy.

Steemers, K., & Yun, G. Y. (2009). Household energy consumption: a study of the role of occupants. Building Research & Information, 37(5-6), 625-637.

Tanabe, S., Arens, E. A., Bauman, F., Zhang, H., & Madsen, T. (1994). Evaluating thermal environments by using a thermal manikin with controlled skin surface temperature.

Veselý, M., Molenaar, P., Vos, M., Li, R., & Zeiler, W. (2017). Personalized heating–Comparison of heaters and control modes. *Building and Environment*, *112*, 223-232.

Watanabe, S., Melikov, A. K., & Knudsen, G. L. (2010). Design of an individually controlled system for an optimal thermal microenvironment. Building and Environment, 45(3), 549-558.

Wienert, V., Sick, H. and zur Mühlen, J. (1983) '[Local thermal stress tolerance of human skin].', Anästhesie, Intensivtherapie, Notfallmedizin, 18(2), pp. 88–90.

Wyon, D. P., Larsson, S., Forsgren, B., & Lundgren, I. (1989). Standard procedures for assessing vehicle climate with a thermal manikin (No. 890049). SAE Technical Paper.

Zhai, Y., Zhang, H., Zhang, Y., Pasut, W., Arens, E., & Meng, Q. (2013). Comfort under personally controlled air movement in warm and humid environments. Building and environment, 65, 109-117.

Zhang, H., Arens, E., Kim, D., Buchberger, E., Bauman, F., & Huizenga, C. (2010). Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system. Building and Environment, 45(1), 29-39.

WORKSHOP 9

Using Statistics for Thermal Comfort Data

Invited Chairs:
Jane Galbraith and Rex Galbraith

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Moving beyond averages: variations in reported thermal comfort

Stephanie Gauthier[1] and DespoinaTeli[2]

[1] Sustainable Energy Research Group, Faculty of Engineering and the Environment, University of Southampton, SO17 1BJ, United Kingdom s.gauthier@soton.ac.uk;
[2] Department of Architecture and Civil Engineering, Chalmers University of Technology, SE-412 96, Göteborg, Sweden teli@chalmers.se

Abstract: Thermal comfort research characterises group thermal perception using averages. This approach overlooks the value of analysing variation as a dependent variable characterising groups' state of comfort. In this paper, we reviewed the results of 219 surveys carried out in five schools in the UK and in Sweden between 2011 and 2016. Results show that pupils' thermal sensation and preference votes varied more at moderate indoor operative temperature. This result suggests that pupils may have a greater range of adaptive opportunities, including clothing, in moderate environments. Substantively, reviewing the spread of the thermal comfort is critical to unpick behavioural, psychosocial and physiological mechanisms. Furthermore, results are significantly different while analysing the central tendency or spread of comfort votes. For example, there is no difference in comfort votes' central tendency between surveys carried out during the heating seasons and the non-heating seasons but there is a significant difference in the spread, indicating the need for multilevel analysis. Methodologically, reviewing the spread of thermal comfort is also critical to establish the data analysis method. With recent advances in surveys' tools allowing larger datasets to be gathered at individual and group levels, it is essential to review the range of analysis methods.

Keywords: thermal adaptation, averages, variability, school buildings, children's thermal comfort

1. Introduction

Thermal comfort studies are based on occupants' assessment of the thermal environment using subjective judgement scales. Two commonly used scales are: (i) the 7-point scale of perceptual judgement [hot, warm, slightly warm, neutral, slightly cool, cool, cold] and (ii) the scale of thermal preference with 7, 5, or 3 degrees [7 degrees: much warmer, warmer, slightly warmer, neither warmer nor cooler, slightly cooler, cooler, much cooler] (ISO, 2001).

Plots of comfort or preference votes against temperature typically present considerable dispersion, especially when the data comes from field surveys. The large variation in comfort votes at the same temperature have been attributed to the fact that the comfort vote is a response to multiple environmental and social stimuli that the respondents experience and the overall differences between individuals (Nicol et al., 2012). Shipworth et al. (2016) point out that based on measurement theory part of the observed variance in comfort votes will be due to measurement error, whilst other possible explanatory factors include biological drivers (e.g. metabolism, age, weight); climatic, cultural and personal experiences and psychological, cognitive and emotional drivers. Even though there is a strong theoretical basis of the importance of variation in thermal sensation, it has not been adequately explored. The mean value of comfort vote is the most used statistic in thermal comfort analyses, but it can hide information about the data's scatter (Nicol et al., 2012). Standard deviation, which describes how much the comfort vote varies around the mean, is typically briefly mentioned or plotted without further analysis. Humphreys et al. (2007) calculated the mean residual standard deviation from three large databases at 1.07 scale units on a 7-point thermal sensation scale, which corresponds to a temperature difference of 2.7°C. This result highlights interpersonal differences in thermal sensation, which points out a need for further analysis.

The aim of this paper is to investigate the relationship between the variance in thermal sensation and preference vote and a number of variables which affect thermal comfort, such as gender, clothing level, indoor operative temperature, indoor relative humidity and outdoor running mean temperature. The analysis aims to extract information hidden in the data's variance that could help to better understand human comfort and adaptation.

2. Method

2.1. The dataset

This paper reviews the results of 219 surveys carried out in five schools in the UK and Sweden. Details of the sample are summarised in Table 1. Schools U1, U2, U3 and U4 are located in Southampton (UK) while school S1 is located in Gothenburg (Sweden). Both locations have a Köppen Climate Classification Cfb (Oceanic). The majority of the surveys in Southampton were conducted in spring/summer (April-July) and a few in autumn (October). Typical monthly outdoor temperatures during these months range between 8 and 17°C (1961–1990 averages). In Gothenburg, surveys were conducted in winter (December-April) and spring/summer (May-June). Typical average temperatures for the winter months range between -1 and 6°C, whilst in May and June these are 11.5°C and 15.5°C respectively. In the Swedish sample, April is included in the winter period due to the low outdoor temperatures and the fact that heating was constantly on. In the UK, in April heating was used in a few instances and only for a couple of hours based on the weather. However, the surveys were conducted when heating was 'off' therefore, in this case, April is included in the non-heating season.

Table 1. Characteristics of the sample

Countries	Schools no.	Classrooms no.	Surveys no.	Questionnaires no.	Seasons	No-heating season survey no.
UK	U1	8	48	1,314	No-Heating	48
	U2	11	69	1,676	No-Heating	69
	U3	6	8	214	No-Heating	8
	U4	4	4	116	No-Heating	4
Sweden	S1	6	90	2,177	No-Heating & Heating	37
Total		35	219	5,497		166

The majority of the classrooms are (NV) naturally ventilated (heating in winter, free-running, no cooling or mechanical ventilation in summer), and a small number are (MV) mechanically ventilated (no cooling in summer). Surveys (n=219) were carried out between April 2011 and June 2016. In each survey period the visits were planned for every other week. During the classroom visits measurements of the environmental parameters affecting thermal comfort were also taken (air temperature, globe temperature, relative air speed and relative humidity). The instruments were placed as centrally in the classroom as possible and far from heat sources and direct solar radiation. The surveys took place at least 20 minutes after breaks or other non-sedentary activities in order to ensure, as much as possible, consistent metabolic rates throughout the study.

In parallel to environmental monitoring, questionnaires were completed, which applied questions on indoor thermal sensation and preference, self-assessed tiredness level, use of environmental controls, self-estimated clothing and activity levels. The clothing insulation was determined differently in the UK and Swedish samples as in the UK there is a uniform policy whilst in Sweden children (or their parents) can choose their clothing. The questionnaire was answered several times by the same participant in the same classroom at different times and dates. For the purposes of this paper the results of two questions are analysed, Thermal Sensation Vote (TSV) (7-point scale) and Thermal Preference Vote (TPV) (7-point scale), both are referred to as 'comfort votes' in the analysis. These are assumed to be discrete variables.

2.2. Study design

The analysis undertakes a series of inferential tests and regression analysis. Prior to these tests, data 'cleaning' was undertaken and variables were defined.

During data cleaning, it was observed that in some responses there was an inconsistency between the thermal sensation vote (TSV) and thermal preference vote (TPV). This included votes where (TSV + TPV) <−3 or (TSV + TPV) > 3, which reflect cases of disagreement between TSV and TPV, such as where a subject is feeling hot and prefers that it was warmer. Such cases conflict with the approach that thermal sensation votes outside the 3 central categories (-1, 0, 1) express dissatisfaction so one would not want to further enhance that sensation. It was concurred that conflicting votes from young children in a classroom environment could be due to distraction. Following the approach in previous studies in classrooms (Corgnati et al., 2009; Teli et al., 2012; Montazami et al., 2017), 351 inconsistent votes were filtered out of the dataset. The number of questionnaires to be analysed was reduced to N=5,146.

For ethical reasons, we do not know which child completed which questionnaire, the variable 'participant' is undefined. Therefore, the chosen unit of analysis will be the surveys (n=219). As the unit of analysis is the survey, it raises questions in choosing the metric to qualify the surveys' TSV and TPV distributions. Should it be a measure of the central tendency or a measure of the spread? To determine the measure of scale, normality of TSV and TPV distributions of each survey was assessed by applying Shapiro-Wilk test. Results show that for only 30% of the surveys TSV is normally distributed and for 32% of the surveys TPV is normally distributed. The paper will undertake two parallel analyses, the first one using conventional measures of scale as the surveys' mean ($\bar{x}$) and standard deviation ($_{sd}$), and the second analysis using robust measures of scale as the surveys median ($_{M}$) and interquartile range ($_{IQR}$).

Using regression analysis, the paper explores the relationships between TSV and TPV as dependent variables and the six standard thermal comfort independent variables, defined as: indoor operative temperature (t_{op}) (^{o}C), indoor relative humidity (RH) (%), indoor relative air velocity (v_{ar}) (m/s), clothing insulation (I_{cl}) (clo), metabolic rate (M) (met) and running mean external temperature (T_{rm}) (^{o}C). As the questionnaires for each survey were carried out at the same time, all of the environmental independent variables will have the same value for all the questionnaires of one survey. It should be noted that relative air velocity was very low for all surveys (v_{ar}=0.053 ± 0.046). For the independent variable I_{cl}, the paper considers two measures of scale, its mean ($\bar{x}$) and its standard deviation ($_{sd}$). For metabolic rate, it was assumed that pupils were sedentary in most cases and a nominal value of 1.2 met was given to most questionnaires unless the pupils reported otherwise (M=1.2 ± 0.03) . All the variables explored are summarised below:

- 8 dependent variables: $TSV_{\bar{x}}$, TSV_{sd}, $TPV_{\bar{x}}$, TPV_{sd}, TSV_{M}, TSV_{IQR}, TPV_{M} and TPV_{IQR}.
- 7 independent variables: t_{op}, RH, v_{ar}, $I_{cl\,\bar{x}}$, $I_{cl\,sd}$, M and T_{rm}.

3. Results and discussion

The study design calls for participants to complete the same questionnaire at different times/dates, therefore the surveys within each classroom are paired. As the variable ‘participant’ is undefined, the variability between- and within- participants at survey level cannot be assessed. The analysis continued by reviewing the variability between- and within-surveys at classroom level applying repeated measure analysis. During the heating season, the variable ‘classroom’ has a significant effect on thermal sensation and preference, as determined by repeated measure analysis applying a multilevel approach, respectively $\chi^2(5)=13.23$, $p<0.05$ and $\chi^2(5)=27.46$, $p<0.05$. During the non-heating season, the variable ‘classroom’ has also a significant effect on thermal sensation and preference, as determined by repeated measure analysis applying a multilevel approach, respectively $\chi^2(34)=81.35$, $p<0.05$ and $\chi^2(34)=127.40$, $p<0.05$. These results highlight significant variabilities between- and within- surveys at classroom level, therefore the subsequent analysis will review variables by surveys (n=219) and classrooms (n=35).

Only significant relationships ($p<0.05$) and with a least a small effect (Cohen, 1992) are reviewed and discussed in the following sections, many other inferential tests and regression analysis were carried out but their results were not deemed significant.

3.1 Review at classroom level

First, the paper reviews the relationship between the dependent and independent variables at classroom level. Results of the regression analysis show that there is a medium to large effect of mean t_{op} on the central tendency in comfort votes ($\mathrm{TSV}_{\bar{x}}$, $\mathrm{TPV}_{\bar{x}}$, TSV_M and TPV_M) ($p<0.05$ and adjusted $R^2>0.3$) but no other independent variable has an effect. As shown in Figure 1, $\mathrm{TSV}_{\bar{x}}$ and TSV_M increased as indoor operative temperature increased and $\mathrm{TPV}_{\bar{x}}$ and TPV_M decreased as indoor operative temperature increased. As expected, as mean indoor operative temperature increased participants felt on average warmer and preferred to feel on average cooler. However, it is surprising that no other independent variable had a significant effect on the central tendency in comfort votes.

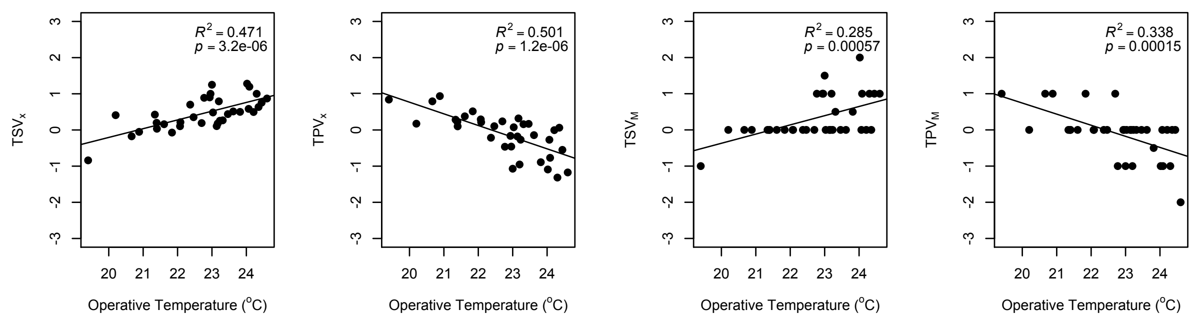


Figure 1. Relationship between mean operative temperature and central tendency of comfort votes at classroom level

In contrast, there is a medium effect of $\mathrm{I}_{\mathrm{cl\ sd}}$ on the spread in comfort votes (TSV_{sd}, TPV_{sd}, TSV_{IQR} and TPV_{IQR}) ($p<0.05$ and $0.22<$adjusted $R^2<0.4$), and a small effect of mean T_{rm} on the same dependent variables ($p<0.05$ and $0.08<$adjusted $R^2<0.25$). The remaining four independent variables, including mean t_{op}, have no effect on the spread in comfort votes. As shown in Figure 2, TSV_{sd}, TPV_{sd}, TSV_{IQR} and TPV_{IQR} decreased as $\mathrm{I}_{\mathrm{cl\ sd}}$ increased. In other words, the variability in comfort votes decreased as participants variability in clothing insulation increased. This result establishes an interesting behavioural adaptation pathway; as people adapt through the use of clothing the variation in comfort votes decreases.

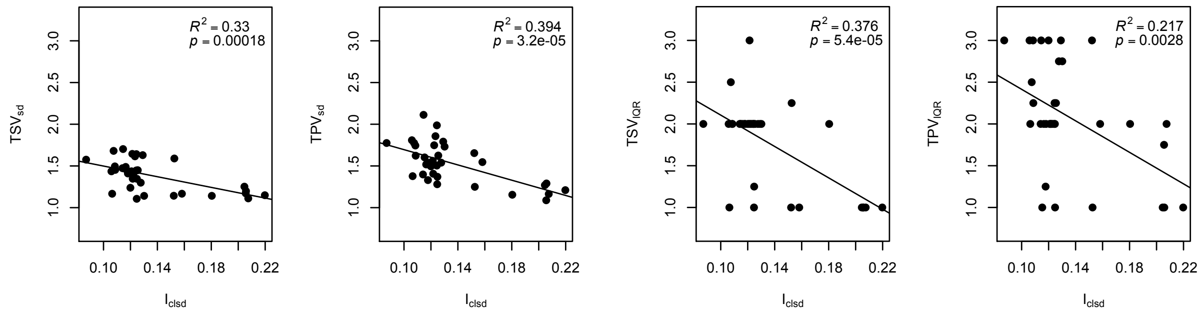


Figure 2. Relationship between the standard deviation of clothing insulation and the spread of comfort votes at classroom level

As shown in Figure 3, TSV_{sd}, TPV_{sd} and TSV_{IQR} increased as mean T_{rm} increased, that is the variability in comfort votes increased as the average running mean external temperature per classroom increased. As it gets warmer, the variation in comfort votes increases. This result suggests that pupil's thermal sensation and preference varied more at higher but moderate[1] outdoor temperatures when they might have access to a greater range of adaptive opportunities including clothing. In this study in schools' environments, pupils increased their clothing level in cold conditions leading to more consistent high clothing insulation value while at moderate temperature there is a larger variation in clothing insulation.

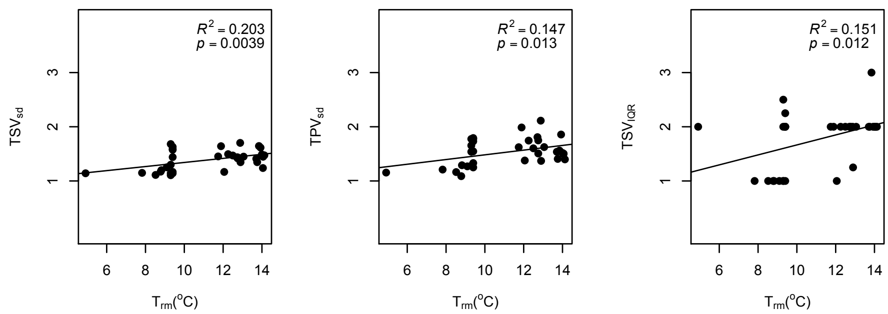


Figure 3. Relationship between the running mean external temperature and the spread of comfort votes at classroom level

3.2 Review at survey level

Prior to the regression analysis, inferential tests were carried out to explore dependent variables differences between countries and heating/non-heating seasons. For the countries, results show that there is no difference in $TSV_{\bar{x}}$, $TPV_{\bar{x}}$, TSV_M and TPV_M but there are significant differences in TSV_{sd} (t(209.95)=-8.6, p<0.05), TPV_{sd} (t(216.78)=-11.96, p<0.05), TSV_{IQR} (U=4562.5, p<0.05) and TPV_{IQR} (U=2388, p<0.05). For the seasons, results show that there is no difference in $TPV_{\bar{x}}$, TSV_M, TPV_M and TSV_{IQR}, but ther are significant differences in $TSV_{\bar{x}}$ (t(119.29)=-2.19, p<0.05), TSV_{sd} (t(114.51)=-4.5, p<0.05), TPV_{sd} (t(137.63)=-6.37, p<0.05) and TPV_{IQR} (U=2388, p<0.05). In summary, most central tendency comfort votes are not different between countries and seasons, but most spread in comfort votes are different between countries and seasons. In light of these results, the following sections will review the relationships between comfort votes and the independent variables at countries and seasons levels. Furthermore, future thermal comfort models may be based on multilevel analysis.

[1] 'Moderate' is used here to describe the indoor environment that is not "extreme" (neither hot nor cold), as used in ISO standard 7730, ASHRAE 55 and thermal comfort literature (Parsons, 2014).

3.2.1 Review of countries' differences

The analysis then reviews the relationships between the dependent and independent variables for the two countries, UK and Sweden. For both countries, results are similar.

There is a medium to large effect of t_{op} on the central tendency in comfort votes ($TSV_{\bar{x}}$, $TPV_{\bar{x}}$, TSV_M and TPV_M) ($p<0.05$ and adjusted $R^2>0.3$). There is also a small to medium effect of $I_{cl\,\bar{x}}$ on the same variables ($p<0.05$ and $0.1<$adjusted $R^2<0.3$). The remaining five independent variables have no effect on the central tendency in comfort votes. Similar to the results at classroom level, as indoor operative temperature increased participants felt on average warmer and preferred to feel, on average, cooler. Beside as participants felt colder and would preferred to feel warmer, their mean clothing insulation increased (see Figure 4). This result establishes that clothing insulation is a behavioural adaptation mechanism to children in the UK and Sweden; as they feel colder and preferred to be warmer, they put on more layers of clothing.

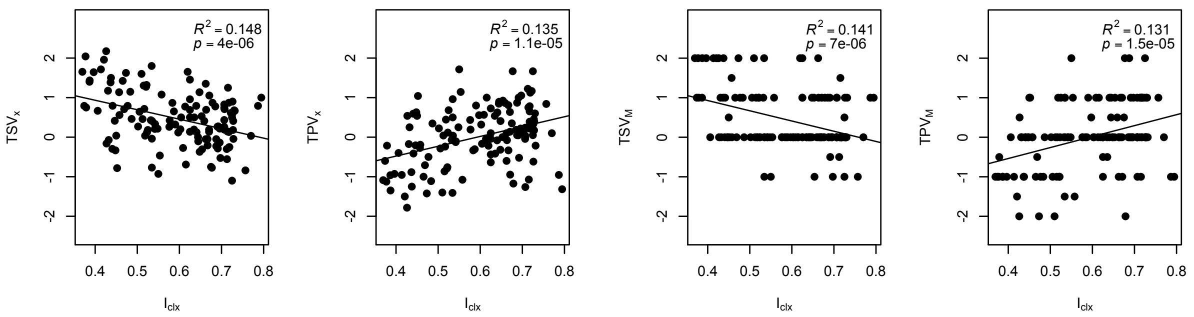


Figure 4. Relationship between mean clothing insulation and [$TSV_{\bar{x}}$, $TPV_{\bar{x}}$, TSV_M and TPV_M] in the UK at survey level

With regard to the spread in comfort votes (TSV_{sd}, TPV_{sd}, TSV_{IQR} and TPV_{IQR}) results are again similar for both countries. The independent variables have no or very small effect on the spread in comfort votes.

3.2.2 Review of heating seasons differences

Finally, the analysis reviews the relationships between the dependent and independent variables for the heating and non-heating seasons. During the heating season, only t_{op} has a small to medium effect on the central tendency in comfort votes ($TSV_{\bar{x}}$, $TPV_{\bar{x}}$, TSV_M and TPV_M) ($p<0.05$ and $0.1<$adjusted $R^2<0.4$). Similar to the results at classroom level (see Figure 1), as indoor operative temperature increased average thermal sensation increased and thermal perception decreased as would be expected; e.g. a student felling warm would prefer to be colder. The remaining six independent variables have no or very small effect on the central tendency in comfort votes during the heating season.

In contrast, during the non-heating season, t_{op} and $I_{cl\,\bar{x}}$ have both a small to large effect on the central tendency in comfort votes ($p<0.05$ and $0.1<$adjusted $R^2<0.5$). Again, as indoor operative temperature increased participants felt on average warmer and preferred to feel on average cooler. Also, similar to the results shown in Figure 4, as mean clothing insulation increased, participants felt on average colder and would prefer to feel on average warmer. The remaining five independent variables have no or small effect on the central tendency in comfort votes during the non-heating season. In summary, clothing insulation is a behavioural adaptation mechanism during the non-heating season.

With regard to the spread in comfort votes (TSV_{sd}, TPV_{sd}, TSV_{IQR} and TPV_{IQR}), there is no relationship between the dependent and independent variables during the heating season.

In contrast during the non-heating season, there is a small to medium effect of t_{op}, RH and $I_{cl\,\bar{x}}$ on TSV_{sd}, TPV_{sd} and TPV_{IQR} (p<0.05 and 0.1<adjusted R^2<0.3).

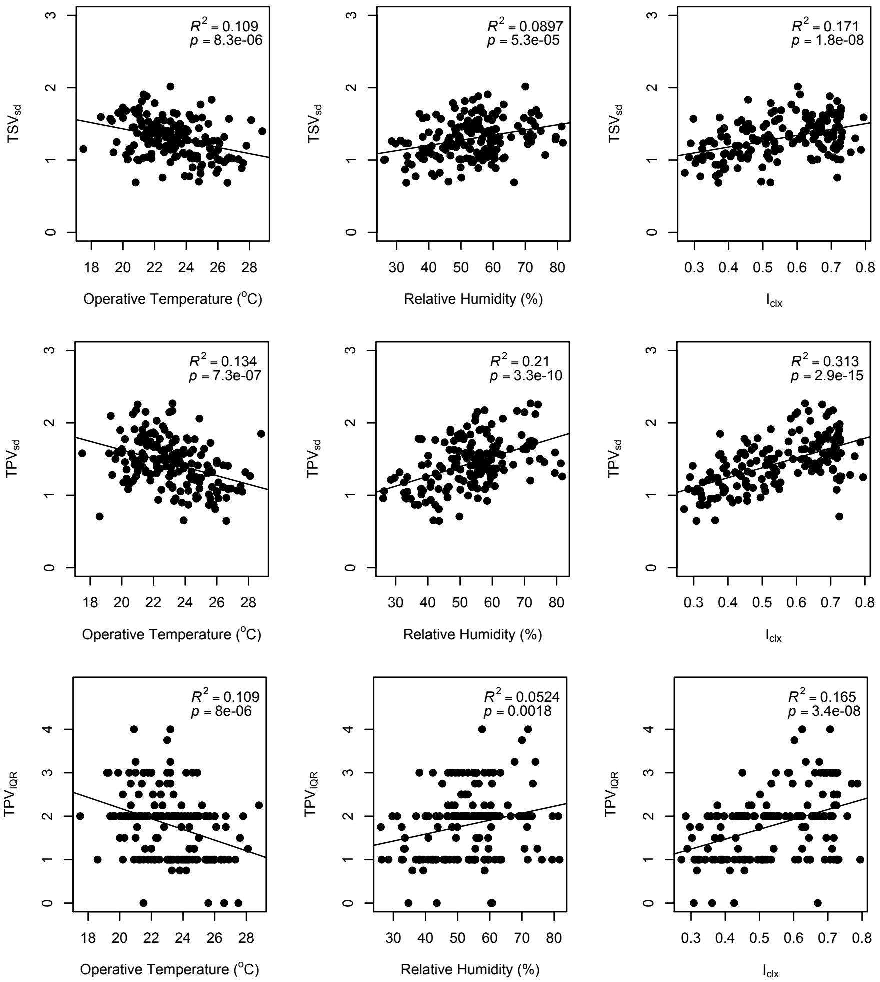


Figure 5. Relationship between [operative temperature, relative humidity and mean clothing insulation] and [TSV_{sd}, TPV_{sd} and TPV_{IQR}] during the non-heating season at survey level

As shown in Figure 5, as operative temperature decreased towards moderate indoor conditions the variability in thermal sensation and preference increased. The increased variation may be due to interpersonal differences in clothing in moderate indoor environments. This is confirmed in the data, as can be seen in Figure 6. As operative temperature increased, the variability of clothing insulation decreased. This is likely due to the more pronounced need for clothing adaptation in warm conditions compared to moderate. In warm conditions, adaptation is necessary to avoid warm discomfort, while in moderate conditions the need for adaptation is less profound, especially in the case of young children who have been found to have underdeveloped immediate adaptive response even in cases where they felt uncomfortable (Teli et al., 2014). In this study, most children lowered their clothing levels in warm conditions to avoid discomfort leading to more consistent low clothing insulations, while at moderate temperatures they did not consider doing so as discomfort was not perceived as similarly critical.

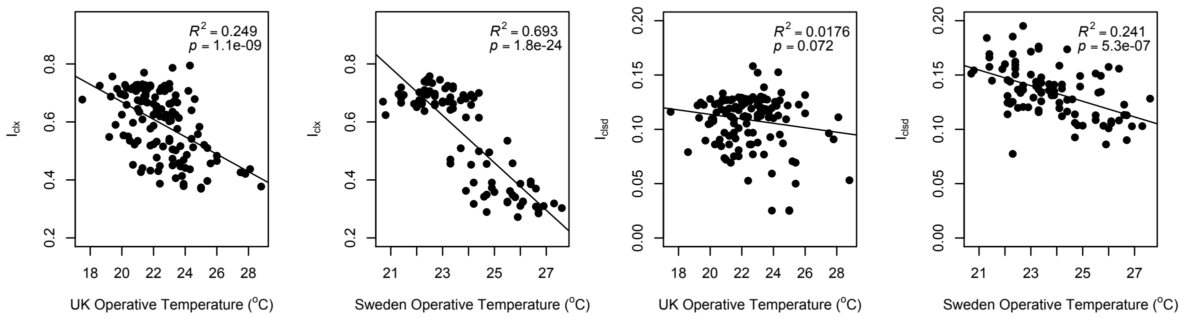


Figure 6. Relationship between operative temperature and [$I_{cl\,\bar{x}}$ and $I_{cl\,sd}$] in the UK and Sweden at survey level

Moreover, weather during the transitional season is variable (see Table 2) and the indoor conditions in naturally ventilated buildings more unpredictable as a consequence, making it more difficult to decide on an appropriate clothing level. This leads to the interpersonal variability in clothing level at moderate indoor temperature, observed in Figure 6.

Table 2. Monthly standard deviation of daily outdoor temperatures for the survey periods

	2011 Southampton	2012 Southampton	2016 Gothenburg
February	-	4.20	2.87
March	2.7	2.17	2.16
April	2.4	1.36	1.86
May	1.2	4.20	3.70
June	2.4	1.73	2.65
July	1.3	2.25	2.27

The increased variation in comfort vote may also be due the personal variations in thermal sensation and preference thresholds related to psychological and physiological adaptation. A high temperature (e.g. 28°C) may be perceived high by most people, but a moderate temperature (e.g. 23 °C) may be perceived as high by some people and neutral by other people. Hence the observed high variability in comfort vote at moderate operative temperatures, and lower variability at higher operative temperatures. This result established the variations in people psychological thermoneutral zone related to different thermal habituation and expectation (Brager and de Dear, 1998). The observed trend in comfort vote variability may also be due to the variation in physiological thermoneutral zone, defined as *"the range of ambient temperatures without regulatory changes in metabolic heat production or evaporative heat loss"* (Kingma, 2012). The physiological thermoneutral zone is influenced by many factors, including body composition, age and gender, which vary from participant to participant.

Figure 5 also shows the relationship between indoor relative humidity and variabilities in TSV and TPV during the non-heating season. As RH increased, TSV_{sd}, TPV_{sd} and TPV_{IQR} increased. RH standard comfort zone is defined as 40 to 70% (CIBSE, guide A, 2015, section 1.3.1.3). As RH went beyond the high threshold, variability in comfort votes increased. An environment with a high relative humidity at operative temperature of 21°C will be perceived very differently than at 28°C. Further study should explore the three-way relationship between variability in comfort votes, relative humidity and operative temperature.

Finally Figure 5 shows the relationship between mean clothing insulation and variabilities in TSV and TPV during the non-heating season. As $I_{cl\,\bar{x}}$ inscreased, TSV_{sd}, TPV_{sd} and TPV_{IQR} increased. As participants increased their clothing insulation level, the variability in comfort vote increased. During the non-heating season, pupils may have felt colder at moderate temperature and increased their clothing level. Furthermore, this study is taking place in primary schools in the UK and Sweden, and most of the non-heating season surveys were carried out in the UK where pupils are required to wear a uniform. This will constrain the range of clothing options available to adapt. Applying behavioural thermal adaptation, pupils increase their level of clothing to the maximum amount allowed when feeling cold. As a result, some pupils may be feeling neutral, while others may still be feeling cold and preferred to be warmer as the uniform does not provide enough insulation. For this reason, during the non-heating season, comfort votes' variability is higher at moderate operative temperatures and for higher clothing levels.

4. Conclusions

The paper reviews the relationships between comfort votes and their standard influencing factors. In reference to the paper by Brager and de Dear (1998) on thermal adaptation, the key findings of this study are summarised in Figure 7 and described as follows:

- Behavioural adaptation: As pupils adapt to cold or warm environments, the variability in thermal insulation decreases. While in moderate environments, the variability in thermal insulation increases. As pupils felt colder and preferred to be warmer, the central tendency of thermal insulation increased.
- Psychological adaptation: Due to thermal habituation and expectation, a moderate operative temperature will be perceived differently by different pupils. In contrast, a very high or very low operative temperature will be perceived similarly by most pupils. This result translates in the initiation of a psychological thermoneutral zone (see Figure 7).
- Physiological adaptation: Due to variations in body composition and gender, a moderate operative temperature will be perceived differently by different pupils. This results relates to the physiological thermoneutral zone introduced by Kingma et al (2012).

This study was carried out in school environments, where pupils' behavioural adaptation opportunities are limited to clothing thermal insulation. In other environments, such as domestic settings, people will have access to a much wider range of adaptive opportunities including change in activity levels and heating controls (Gauthier and Shipworth, 2015). There, the relationship between behavioural adaptation and operative temperature may differ. As shown in Gauthier (2016), the frequency and the intensity in activity level increased as operative temperature decreased.

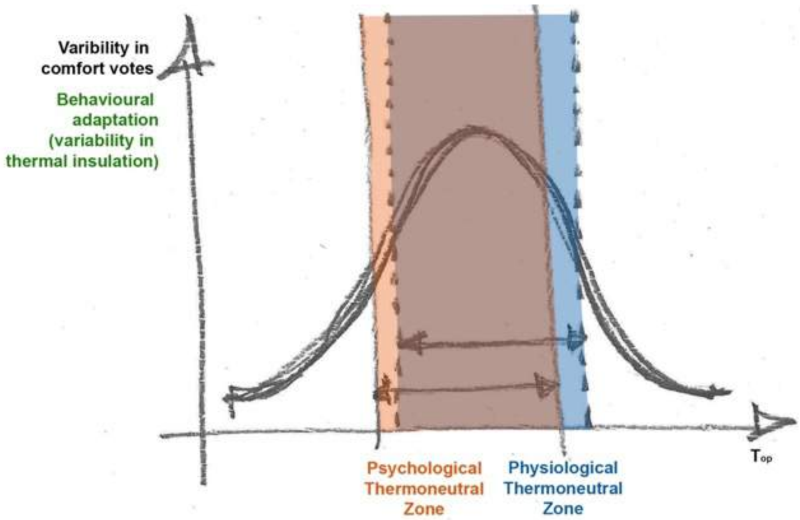


Figure 7. Relationship between operative temperature and variability in comfort votes

To conclude the paper establishes key substantive findings, it is clear that reviewing the spread of TSV and TPV is critical to uncover the effect of thermal adaptation mechanisms. This is also a key methodological finding as to date, thermal comfort research has focused on reviewing metrics of central tendency rather than spread.

In conclusion, the paper demonstrates the value of analysing variations in a large dataset. The recent advances in survey tools, including mobile apps and sensing technologies, enable larger datasets to be gathered at individual and group levels. Individual and group variations should be reviewed in future thermal comfort analysis. Trends and/or features in groups may be detected enabling group-level heterogeneity and thermal adaptation mechanisms to be uncovered. Finally, these variations may be incorporated into new stochastic multilevel thermal comfort models.

5. References

Brager, G. and de Dear, R.,1998. *Thermal adaptation in the built environment: a literature review*. Energy and Buildings, 27, 83-96.

Cohen, J., 1992. *A power primer*. Psychological Bulletin, 112(1), 155-159.

Corgnati, S.P., Ansaldi, R. and Filippi, M., 2009. *Thermal comfort in Italian classrooms under free running conditions during mid seasons: Assessment through objective and subjective approaches*. Building and Environment, 44 (4), 785-792.

Gauthier, S. and Shipworth, D., 2015. *Behavioural responses to cold thermal discomfort*. Building Research & Information, 43(3), 355-370.

Gauthier, S., 2016. *Investigating the propability of behavioural responses to cold thermal discomfort*. Energy and Buildings, 124, 70-78.

Humphreys M.A., Nicol J.F. and Raja I.A., 2007. *Field Studies of Indoor Thermal Comfort and the Progress of the Adaptive Approach*. Advances in Building Energy Research, 1 (1), 55-88.

Iso (2001) EN ISO 10551:2001. *Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales.* Geneva: International Standardisation Organisation.

Kingma B, Frijns A, van Marken Lichtenbelt W., 2012. *The thermoneutral zone: implications for metabolic studies.* Front Biosci (Elite Ed). 4, 1975-198.

Montazami, A., Gaterell, M., Nicol, F., Lumley, M. and Thoua, C., 2017. *Developing an algorithm to illustrate the likelihood of the dissatisfaction rate with relation to the indoor temperature in naturally ventilated classrooms.* Building and Environment, 111, 61-71.

Nicol, F., Humphreys, M. and Roaf, S., 2012. *Adaptive thermal comfort: Principles and practice.* London: Routledge.

Parsons K.C., 2014. *Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort, and performance.* Boca Raton: CRC Press, Taylor & Francis Group.

Shipworth, D., Huebner, G., Schweiker, M. and Kingma, B.R., 2016. *Diversity in Thermal Sensation: drivers of variance and methodological artefacts.* Paper presented at 9th Windsor Conference: Making Comfort Relevant, 07 - 10 Apr 2016. Cumberland Lodge, Windsor, UK.

Teli, D., Jentsch, M.F. and James, P.a.B., 2012. *Naturally ventilated classrooms: An assessment of existing comfort models for predicting the thermal sensation and preference of primary school children.* Energy and Buildings, 53, 166-182.

Teli, D., Jentsch, M.F. and James, P.a.B., 2014. *The role of a building's thermal properties on pupils' thermal comfort in junior school classrooms as determined in field studies.* Building and Environment, 82 (0), 640-654.

Acknowledgments

This work is part of the Energy and Climate Change Division and the Sustainable Energy Research Group (www.energy.soton.ac.uk) on cities and is partly supported by the EPSRC Grant EP/J017698/1 “Transforming the Engineering of Cities to Deliver Societal and Planetary Wellbeing” and EP/K012347/1 International Centre for Infrastructure Futures (ICIF). D. Teli is a VINNMER Fellow supported by VINNOVA (Swedish Innovation Agency), Marie Curie Actions and the Profile ‘Energy in Urban Development’ within the Area of Advance ‘Energy’ at Chalmers University of Technology. Lastly, the authors would like to thank the respondents who participated in this study.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Introducing thermal comfort attitudes, psychological, social and contextual drivers in occupant behaviour modelling with Bayesian Networks

Verena M. Barthelmes[1,2], Rune K. Andersen[1], Yeonsook Heo[3], Henrik Knudsen[1], Valentina Fabi[2], and Stefano P. Corgnati[2]

[1] Technical University of Denmark, DK
[2] Politecnico di Torino, IT
[3] University of Cambridge, UK

Abstract: The acknowledgment of occupant behaviour as a key driver of uncertainty in building energy analysis is today well established. Existing literature highlights the need of carefully addressing human-related interactions with the building envelope and systems. In response to this need, researchers have proposed a number of stochastic models that aim at reflecting occupant behaviour patterns in building energy simulation to bridge the gap between simulated and real energy consumptions in buildings. However, most proposed approaches for modelling occupant behaviour consider time-related factors and physical parameters such as indoor or outdoor environmental variables while less attention is paid to other influential factors such as psychological, social and contextual drivers or individual thermal comfort attitudes and preferences of the occupants. To understand occupant behaviour in a comprehensive manner, these factors should be carefully addressed in upcoming occupant behaviour models. The Bayesian Network framework presents a promising environment for hierarchically and flexibly structuring a large number of explanatory variables that drive the occupant to perform a certain action. This paper describes the development of a theoretical model of occupant's window control behaviour with an extensive set of drivers and highlights the capability and usability of Bayesian Networks to develop such models based on field measurements and information collected through surveys compiled by the building occupants.

Keywords: Occupant behaviour, window control behaviour, Bayesian Networks, residential buildings

1. Introduction

Building occupants and their interaction with the building envelope and systems are responsible for a large share of uncertainty when predicting building energy demand and thermal comfort conditions of the indoor environment (Masoso and Grobler, 2010). Occupants interact with the building in order to meet their comfort criteria by adjusting heating/cooling set-points, lighting levels, windows and sunscreens, or other installed HVAC systems and building envelope features. Existing literature shows that there are high discrepancies in terms of energy demand between buildings with a similar layout and same climatic conditions (Andersen et al., 2007). Indeed, humans perceive the indoor environment in different ways due to a multiple set of factors, have different motivations and habits or can even be conditioned by a series of barriers (e.g. social or economic factors) that restrain them from performing a certain action, even though they feel the need to change the conditions of the indoor environment.

Occupant's action of window opening/closing has an important impact on building energy use and indoor environmental quality (IEQ) by changing the amount of fresh air to the building. Several studies have been carried out to develop stochastic models for predicting the occupant's interaction with the windows (Rijal et al., 2008; Haldi and Robinson, 2009; Schweiker et al., 2012; Zhang and Barrett, 2012; Andersen et al., 2013; Andersen et al., 2016).

These models are based on statistical algorithms to predict the probability of a specific condition or event, such as the window state or the window opening/closing action, given a set of environmental or other influential factors. Borgeson and Brager (2008) provide an extensive summary of the literature on modelling studies for predicting occupants' window control behaviour. In some models, temperature is considered as the most important driver (Warren and Parkins, 1984; Rijal et al., 2008) although there is no consensus about whether indoor or outdoor temperature is dominant in determining the behaviour. Most models based on datasets including CO_2 concentration conclude that CO_2 is a dominant driver in residential buildings (Fabi et al., 2012; Andersen et al., 2013; Fabi et al., 2015; Calì et al., 2016). Other models use time-related factors such as the time of the day and season or the current window state as key variables to predict window control actions (Pfafferott and Herkel, 2007; Haldi and Robinson, 2008; Yun and Steemers, 2008).

However, in order to model window control behaviour – or occupant behaviour in general – in a comprehensive manner, it is necessary to explore a more extensive set of factors that drive the occupant to perform a certain action (Schweiker, 2017). Fabi et al. (2012) highlight that much is still unknown about the motivation of building occupants to interact with the building envelope and systems. Hence, they highlight that, next to physical and time-related factors, it is necessary to take into account "individual" factors of occupants, such as the personal background, energy-related attitudes, perception or personal preferences related to the indoor environment. Also the physiological condition of the occupant plays an important role, such as age, gender or health conditions. Fabi et al. (2012) also stress the importance of social driving forces depending on household composition and the interaction between household members (e.g. which household member determines the thermostat set-point or the opening/closing of windows.). Social norms in office environments are investigated by D'Oca et al. (2017) through an extensive survey framework. Wei et al. (2014) identified 27 drivers that have been evaluated in previous behavioural studies and showed that at present none of them can be identified confidently as having no influence. Next to physical and time-related drivers, the authors list occupant age, gender, culture/race, educational level, social grade, household size, family income, thermal sensation, perceived IAQ and noise, health, heating price, and energy use awareness as potential driving factors.

In this context, this paper develops a theoretical model of occupant's window control behaviour with an extensive set of drivers, and discusses ways to develop such models, particularly with use of Bayesian Networks based on extensive field measurements and contextual information from 47 Danish Dwellings. The contextual information was collected through a tailored survey framework that included questions for understanding occupants' individual comfort attitudes and preferences, physiological factors, social factors and norms, perceived control and psychological factors, motivations and habits related to window control behaviour, and preferences on adaptive opportunities (e.g. sequence of actions that occupants perform when they feel hot/cold).

2. Introducing an extensive set of drivers with a tailored Survey Framework

As mentioned previously, most existing studies directly correlate occupants' interactions with the building envelope and systems to physical parameters, such as environmental variables, or time-related parameters (e.g. time of the day). As shown in Figure 1, the behavioural process is influenced by a number of other factors – or "drivers" (Fabi et al., 2012) (Schweiker and Shukuya, 2009) – that have effect on an individual's perception and satisfaction of the indoor environment and on their motivation to change the indoor environmental conditions. The control intention, for instance, can also be conditioned by social and economic factors or norms, or the limited knowledge of how to interact with the building controls (Ajzen and Madden, 1986)(D'Oca et al., 2017)(Mulville et al., 2017)(Chatterton, 2011). Next to traditional field measurements of environmental parameters and information on building characteristics, survey-based information can be introduced in the modelling process to obtain a more accurate picture of behavioural patterns. In this study, these additional factors are investigated by means of a tailored interdisciplinary survey framework for 47 Danish Dwellings.

The interdisciplinary survey framework was assessed to collect detailed information on the occupants regarding: (1) individual comfort attitudes and preferences, (2) physiological factors and individual characteristics (e.g. gender, age, height, weight, smoking habits), (3) social factors (e.g. education, household composition, household income), (4) perceived control and psychological factors (e.g. satisfaction of control options, knowledge of control options, interaction frequency with controls, safety), (5) motivations and habits related to window control behaviour, and (6) adaptive opportunities (e.g. sequence of actions that occupants perform when they feel hot/cold). Since building system characteristics and ethnical origin were similar in all households, information related to these factors were excluded from the survey framework. The results of survey responses shown in this paper refer to a reduced sample size of 35 individuals. Furthermore, it is worth noting that the survey was distributed in Danish language, this paper reports translations of the questions to English language.

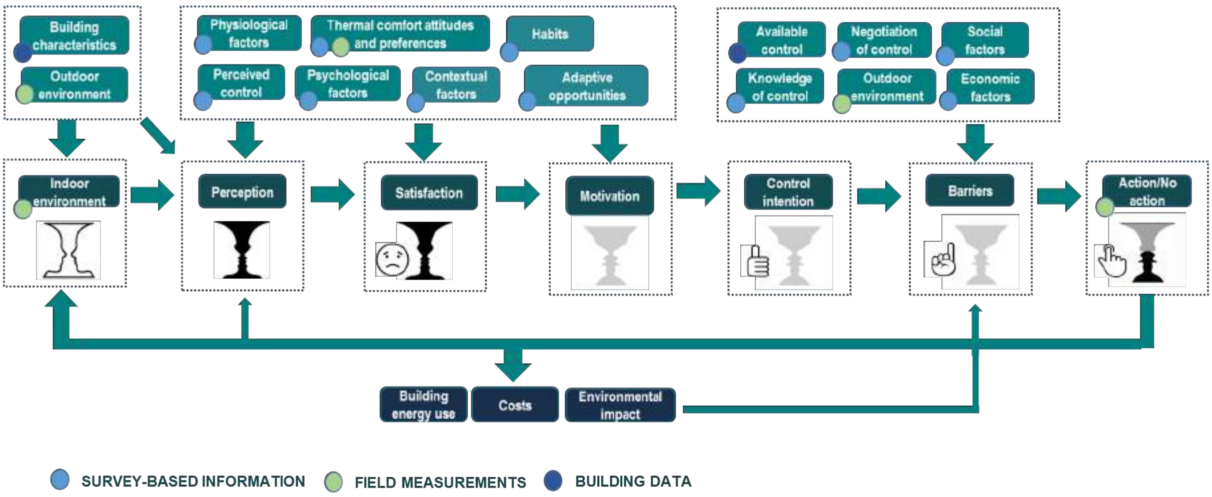


Figure 1. Behavioural process and associated variables identified for data collection

2.1. Individual comfort attitudes and preferences

The first section of the survey addresses the occupants' perception of the indoor environment and their individual preferences. The respondents were requested to indicate their perception and satisfaction of thermal, visual, and acoustic environment and Indoor Air Quality (IAQ). The perception was indicated on a continuous seven-point scale (Figure 2), similar to the Predicted Mean Vote (PMV) thermal scale (Cen, 2007), and the respondents' satisfaction was indicated on a Visual Analogue Scale (VAS) with "Very unacceptable" on one end and "Very acceptable" on the other. This subjective data will be analysed together with field measurements in order to investigate differences in individual perception of the indoor environment due to individual physiological characteristics. Furthermore, the preferences of individual occupants were elicited by asking them how much they agree or disagree with comparative statements. Table 1 summarises the survey questions of the first section. Figure 3 and Figure 4 report two examples of data that show relative priorities associated with indoor environmental aspects that impact window control behaviour. Figure 3 highlights a significant spread in the survey answers when it comes to thermal vs. IAQ-related preferences of the indoor environment that might influence window and/or thermostat control. Furthermore, Figure 4 compares preferences related to IAQ, thermal comfort, noise levels and energy costs.

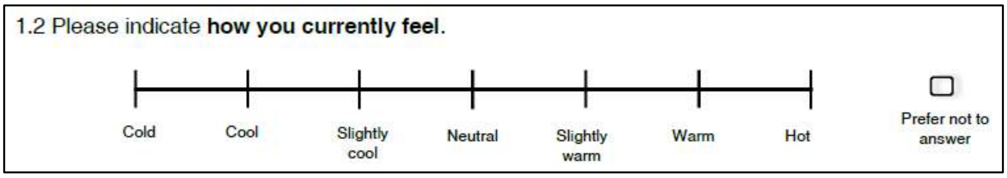


Figure 2. Example: Question for establishing occupants' perception of the indoor environment.

Table 1. Survey section 1: Individual comfort attitudes and preferences

Code	Survey question	Scale
1.1	Please indicate the date and the exact starting time in which you are compiling the survey	-
1.1.1	What kind of activity were you doing shortly before starting to compile the survey?	Multiple choice
1.2	Please indicate how you currently feel	Cold-hot continuous 7-point scale
1.3	Do you currently feel air movement around you?	Yes/No
1.3.1	If yes, how acceptable is it?	VAS Very unacceptable-very acceptable
1.4	Please indicate how you are currently dressed	Nude-winter clothes 7 point scale
1.5	Please describe the lighting level around you	Very dim-very bright - continuous 7-point scale
1.6	How satisfied are you with the amount of light around you?	Very unsatisfied - very satisfied – VAS
1.7	Please describe the air around you	Very stuffy - very fresh - continuous 7-point scale Very humid – very dry - continuous 7-point scale
1.8	How satisfied are you with the air quality around you?	Very unsatisfied - very satisfied – VAS
1.9	Please describe the noise level around you	Very silent – very noisy - continuous 7-point scale
1.9.1	If it is noisy, where does the noise come from?	Multiple choice
1.10	How satisfied are you with the noise level around you?	Very unsatisfied - very satisfied – VAS
1.11	Finally, please indicate your current overall satisfaction with the indoor environment	Very unsatisfied - very satisfied – VAS
2	**How important are the following to you:**	
2.1	Not being too cold or too warm	Very unimportant – very important - continuous 7-point scale
2.2	Absence of drafts	Very unimportant – very important- continuous 7-point scale
2.3	To have good lighting conditions	Very unimportant – very important - continuous 7-point scale
2.4	Absence of noise	Very unimportant – very important - continuous 7-point scale
2.5	To have fresh air	Very unimportant – very important - continuous 7-point scale

2.6	How much do you agree/disagree with the following statements	
2.6.1	"When it is cold outside, I rather feel a little cold to get some fresh air"	Strongly disagree – strongly agree - continuous 5-point scale
2.6.2	"I can accept some noise from outdoors to have some fresh air"	Strongly disagree – strongly agree - continuous 5-point scale
2.6.3	"I rather feel a little cold in order to save some on the heating bill"	Strongly disagree – strongly agree - continuous 5-point scale
2.6.4	"When I open windows, I think about higher energy costs for heating"	Strongly disagree – strongly agree - continuous 5-point scale
2.6.5	"I can accept a slightly bad indoor air quality in order to save some energy costs"	Strongly disagree – strongly agree - continuous 5-point scale
2.6.6.	"My first priority is being comfortable with the temperature and air quality, I don't worry so much about energy costs"	Strongly disagree – strongly agree - continuous 5-point scale
2.6.7	"When I open/close windows and adjust the thermostat, I think about my environmental impact"	Strongly disagree – strongly agree - continuous 5-point scale
2.6.8	"When I open the windows, I usually turn down the heating"	Strongly disagree – strongly agree - continuous 5-point scale

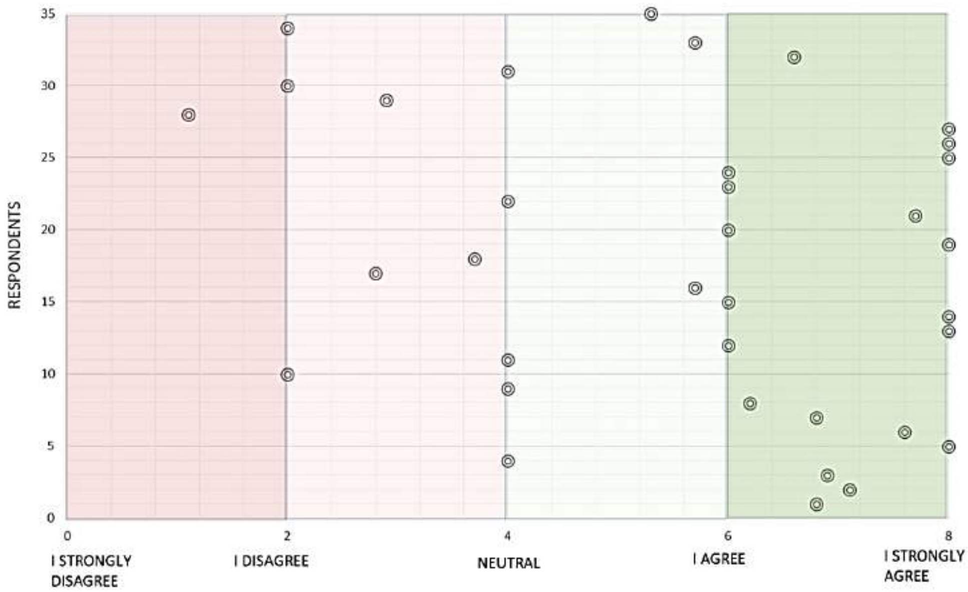


Figure 3. Survey responses to Q2.6.1 "I rather feel a little bit too cold in order to have fresh air".

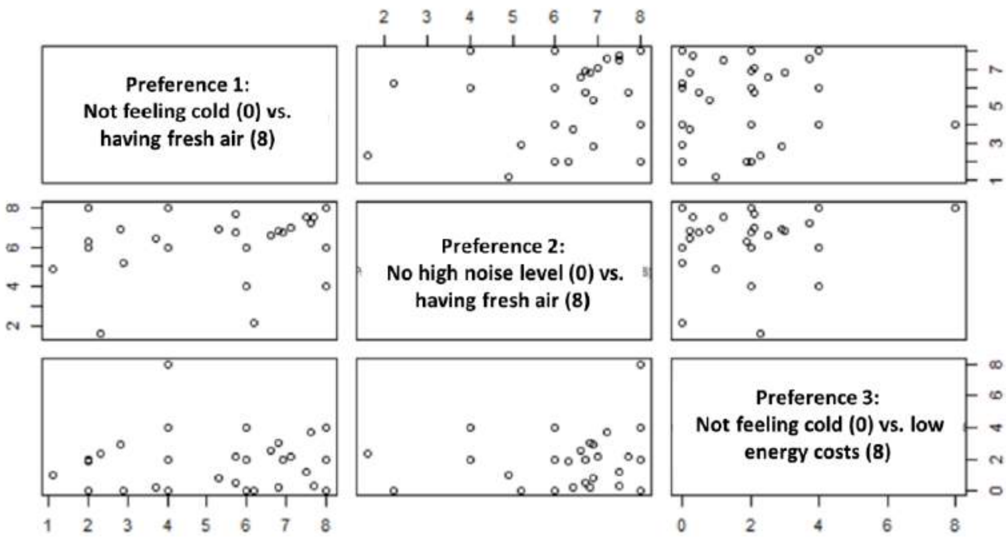


Figure 4. Preferences based on Q2.6.1-3.

2.2. Physiological factors

The second section of the survey aims to gain a deeper knowledge on the physiological characteristics of the occupants. A number of existing studies found that occupants' gender and age influence the individuals' perception of the indoor environment and comfort attitudes (Kingma and Van Marken Lichtenbelt, 2015)(Wei et al., 2014). However, consensus has not been reached about whether gender difference has an impact on the perception of thermal environment (Fanger, 1973). As a health-related question, we asked the occupants if they had any smoking habits, but no further questions about illnesses or other health-related conditions were made due to privacy reasons. The questions related to this section are summarised in Table 3.

Table 2. Survey section 2: Individual comfort attitudes and preferences

Code	Survey question	Scale
3.1	Please indicate your gender	Multiple choice
3.2	Please indicate your age	
3.3	Please indicate your height	-
3.4	Please indicate your weight	-
3.5	Do you smoke?	Multiple choice
3.5.1	Do you smoke inside your house?	Multiple choice
3.5.2	Do you open windows to get rid of tobacco smoke?	Multiple choice

2.3. Social and economic factors

This section provides a deeper insight on energy-related social norms in the household, the household composition itself and economic factors, such as household income and job categories. Extensive studies have shown that the economic level of occupants showed significant effect on the thermal sensation, preference, acceptance and neutrality (Indraganti and Rao, 2010)(Wei et al., 2014). The effect of social and economic norms on thermal comfort will be investigated on the basis on the data collected by the questions summarised in Table 3.

Table 3. Survey section 3: Social and economic factors

Code	Survey question	Scale
4.1	In a typical month, for how long do you live in the household this survey was sent to?	Multiple choice
4.2	Please indicate the total number of adults (including yourself) that in a typical month live in the household (Always, more than half of the time, ca. half of the time, less than half of the time)	-
4.3	Please indicate the total number of children that in a typical month live in the household (Always, more than half of the time, ca. half of the time, less than half of the time)	-
4.4	Please describe your education	Multiple choice
4.5	Please describe your job category	Multiple choice
4.6	Please indicate the monthly household net income	Multiple choice
4.7	Who usually controls the temperature settings in your home?	Multiple choice
4.8	Who usually opens the windows in your home?	Multiple choice
4.9	Who usually closes the windows in your home?	Multiple choice
4.10	Which and how many of the following domestic appliances are used in your home?	Multiple choice

2.4. Perception, satisfaction, and activeness of control

This section of the survey addresses control-related information. In this survey, no further information on available controls was required since control layouts were similar in all households. The respondents were asked if they had any difficulties in operating the control systems or, alternatively, they could indicate that they did not know how to use them. Several studies have shown that perception and satisfaction of control options directly influence perception and satisfaction of the indoor environment (Ajzen and Madden, 1986)(Toftum, 2010; Wei et al., 2014). Questions in this section can be found in Table 4. Figure 5 shows that all respondents reported to interact with the windows at least one time per day. In particular, 37% of respondents stated to open or close windows two times/day.

Table 4. Survey section 4: Perception, satisfaction, and activeness of control.

Code	Survey question	Scale
5.1	**How difficult is it for you to use the…?**	
5.1.1	Thermostat	Very difficult – very easy – 7 point continuous scale
5.1.2	Windows	Very difficult – very easy – 7 point continuous scale
5.1.3	Shading devices	Very difficult – very easy – 7 point continuous scale
5.2	**How satisfied are you with the control options of the…?**	
5.2.1	Thermostat	Very unsatisfied – very satisfied – 7 point continuous scale
5.2.2	Windows	Very unsatisfied – very satisfied – 7 point continuous scale
5.2.3	Shading devices	Very unsatisfied – very satisfied – 7 point continuous scale
5.3	Overall, how satisfied are you with the control options in your home?	Very unsatisfied – very satisfied – 7 point continuous scale
5.4	**In the last 14 days, how often did you operate the...?**	
5.4.1	Thermostat	Multiple choice
5.4.2	Windows	Multiple choice
5.4.3	Shading devices	Multiple choice
5.4.4	Ventilation slots	Multiple choice

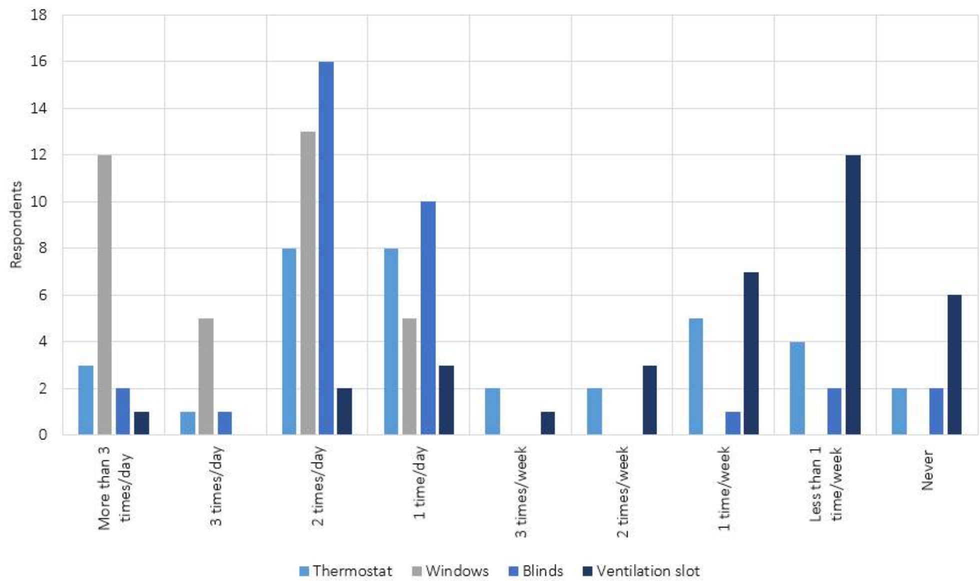


Figure 5. Survey responses to Q5.4 – Activeness of control.

2.5. Motivation and habits for window control behaviour

In this section, the occupants were asked about their motivations or usual habits when they perform a window control action (Table 5) in relation to certain activities (e.g. sleeping, cooking, shower) and certain times of the day (e.g. leaving home, coming back home). This included psychological factors, such as closing the windows for safety reasons and the use of theft protection. In particular, 71% of survey respondents stated that they always close windows for security reasons, while 26% reported that they sometimes close windows for security reasons. Figure 6 shows that more than 70% of the respondents stated to open the window in all rooms to let fresh air in. Other motivations were the prevention of mould growth on surfaces, especially in the bathroom. Respondents also reported that they open windows during or after certain activities: 63% of the respondents reported opening window actions in the bedroom when they wake up, 77% of the respondents declared to open windows in the kitchen after cooking, and more than 90% of the respondents opens windows after a shower. Interestingly, only 7% of the respondents reported opening a window to change the indoor temperature. As regards window closing actions, the two strongest motivations were the change of indoor air temperature (too cold) and leaving home (Figure 7).

Table 5. Survey section 5: Motivation and habits for window control behaviour.

Code	Survey question	Scale
6.1	Why and where do you usually open windows?	Multiple choice for different rooms
6.2	Why and where do you usually close windows?	Multiple choice for different rooms
6.2.1	Do you close windows for safety reasons?	Multiple choice for different rooms

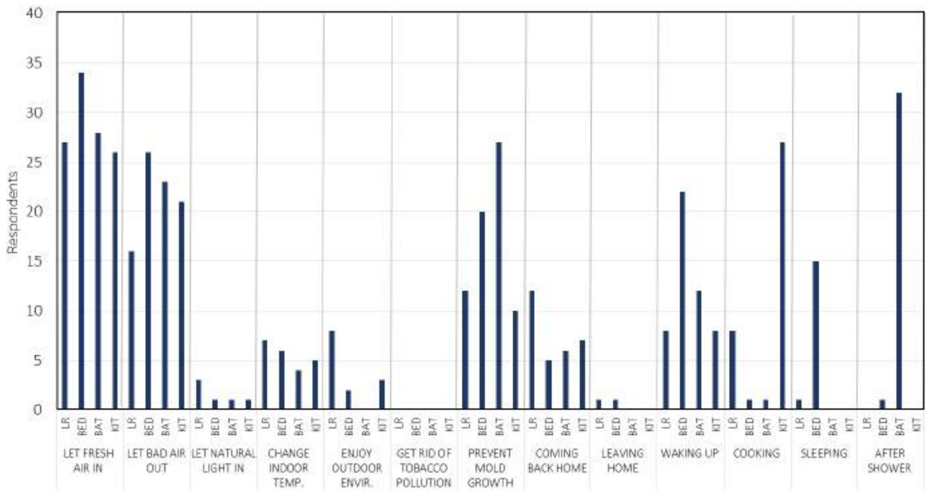


Figure 6. Survey responses to Q6.1: Why do you usually open windows and where? (LR=Living room, BED=Bedroom, BAT=Bathroom, KIT=Kitchen)

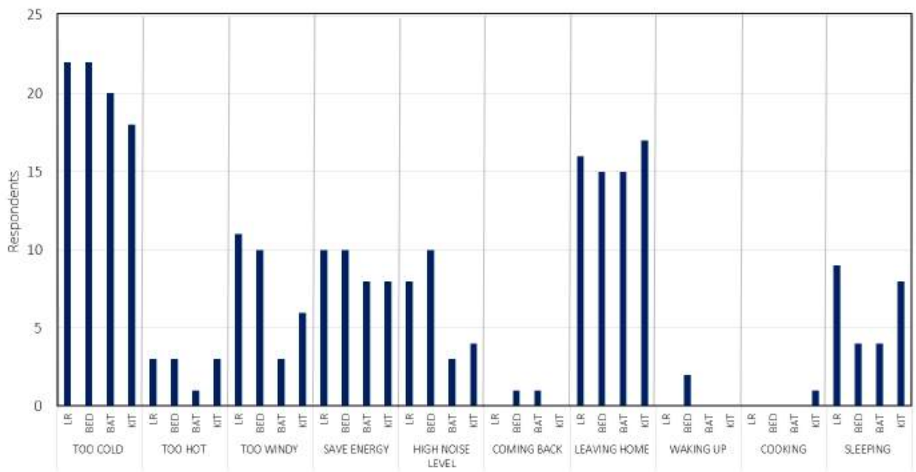


Figure 7. Survey responses to Q6.2: Why do you usually close windows and where? (LR=Living room, BED=Bedroom, BAT=Bathroom, KIT=Kitchen)

2.6. Adaptive opportunities

This section addresses adaptive opportunities that respondents would undertake if they found themselves in particular environmental conditions. In detail, the occupants were asked to indicate if and in which sequence they would perform certain adaptive actions to improve their condition of discomfort (feeling too hot or too cold) (Table 6). Figure 8 shows what the respondents thought they would do when feeling hot during the heating season. The first actions they reported were turning down the heating, removing layers of clothing, and open the window.

Table 6. Survey section 6: Adaptive opportunities.

Code	Survey question	Scale
7.1	Think of a situation in your home, in which you felt feel too hot and it is cool outside. (e.g. a cool summer day), which action would you perform first? Please number the actions you performed in sequence (only the ones that apply) (e.g. __First action, __second action).	Multiple choice
7.2	Think of a situation in your home, in which you feel too cold, and it is cool outside (e.g. a cool summer day), which action would you perform first? Please number the actions you performed in sequence.	Multiple choice
7.3	Think of a situation in your home, in which you feel too hot and it is warm outside (e.g. a warm summer day), which action would you perform first? Please number the actions you performed in sequence.	Multiple choice
7.4	Think of a situation in your home, in which you feel too cold and it is warm outside (e.g. a warm summer day), which action would you perform first? Please number the actions you performed in sequence.	Multiple choice

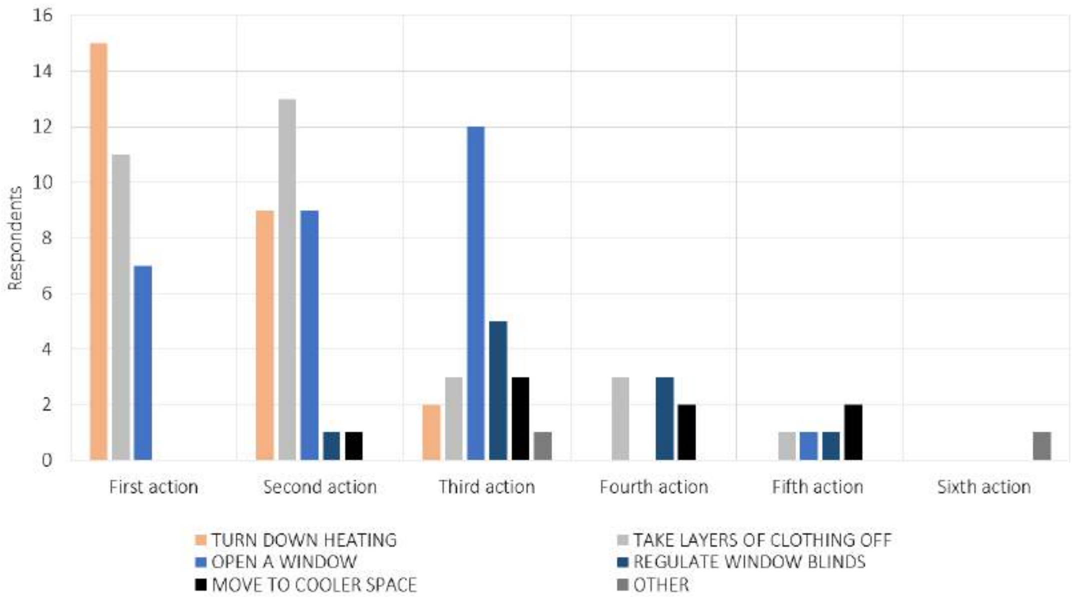


Figure 8. Example: Survey responses to Q7.1 – Adaptive opportunities.

3. Development of a theoretical model for window control behaviour

Figure 8 shows a multi-layered theoretical model that introduces individual preferences, psychological, social and other drivers investigated by means of the above presented survey questions (codes are indicated in Figure 9 and Tables) for modelling occupant behaviour in a more comprehensive manner. In particular, the layers that compose the theoretical model structure are the following:

- **“Horizontal” survey-based layers related to comfort attitudes, preferences, perception and satisfaction of the indoor environment**
  - Physiological characteristics of the occupants
  - Individual preferences on the indoor environment
  - Perception of the indoor environment
  - Satisfaction of the indoor environment
- **“Vertical” field measurement-based layers**
  - Indoor environmental variables
  - Outdoor environmental variables
  - Time-related factors
  - Occupant-related factors (clothing level, activity level)
- **Other influencing factors layer with an extensive set of drivers/barriers**
  - Habits
  - Building characteristics
  - Social and economic factors
  - Psychological factors
- **Control systems layer**
  - Knowledge of control
  - Perceived control
  - Satisfaction of control
  - Interaction level with controls
- **Adaptive opportunities layer**
- **“Target”: Action layer**
  - Window opening control
  - Window closing control

The perception layer includes votes of the respondents on the thermal, visual and acoustic environment as well as on the Indoor Air Quality. The votes on the indoor environmental quality are influenced by a number of factors from the measurement layer, such as indoor/outdoor environmental variables, occupant-related variables, and time-related factors. As an example, the Thermal Sensation Vote depends on influencing factors as indicated in the EN15251 standard (Cen, 2007), which include environmental factors (air temperature, mean radiant temperature, air speed and humidity) and occupant-related factors (metabolic rate and clothing level). Additionally, in this model, the perception layer also depends on physiological characteristics (e.g. gender, age, weight) of the occupants and individual preferences on environmental comfort, as well as the relation of the occupant with the control systems (knowledge of control, perceived control, satisfaction of control, and interaction level with controls)(Paciuk, 1990). Based on the perception votes of the indoor environment, the occupants express levels of satisfaction in terms of thermal, IAQ, visual, and acoustic environment. The level of satisfaction with the indoor environmental quality is a key factor that drives the occupant to perform a certain action, such as a window opening or closing control action (target action layer). At the same time, next to the perception and satisfaction of the indoor environment, a layer containing other influencing factors, such as habits, building characteristics, psychological factors, and social/economic factors might influence the occupant to interact/or not to interact with the window. These factors, in turn, can also be influenced by factors located on the measurements layer. As an example, habits of window control behaviour during certain activities (e.g. sleeping, cooking) can be related to certain times of the day. Finally, the decision of performing a window control action is influenced by the possibility of ceasing different adaptive opportunities (e.g. active body adaptation, thermoregulation, environmental direct control) according to personal preferences and control options. In line with this, it is worth noting that next steps should extend the action layer to include additional control options, such as thermostat control or window blinds regulation.

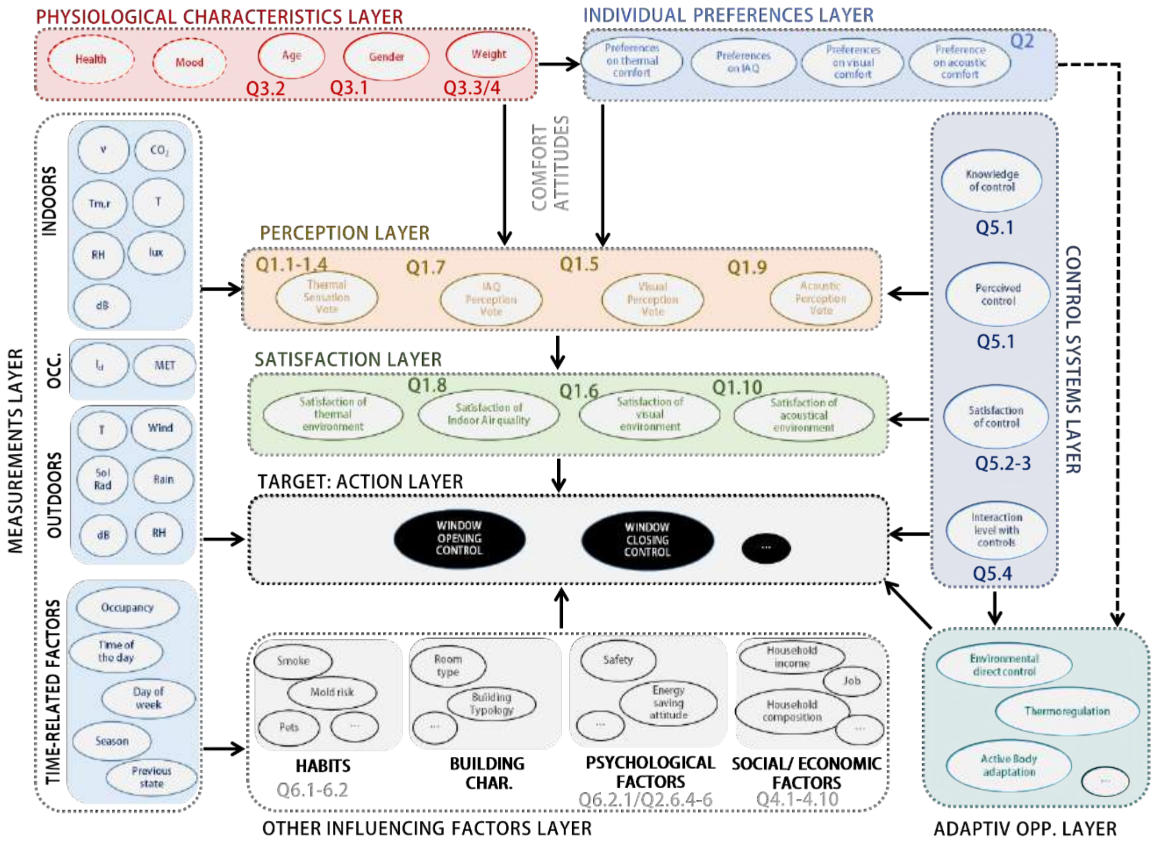


Figure 9. Proposal of a multi-layered theoretical model for window control behaviour.

4. Discussion

The proposed theoretical model takes into account an extensive set of factors on different layers that might drive the occupants to perform one of the targeted window control actions. The Bayesian Network (BN) framework represents a promising modelling method to reflect the theoretical model as it allows for capturing the probabilistic dependencies between the target ("action") layer and an extensive number of driving factors structured in a hierarchical manner. BNs are graphical models that represent a set of variables and their conditional dependencies via a Directed Acyclic Graph (DAG). In detail, nodes represent the variables, and the dependencies between variables are depicted as directional links corresponding to conditional probabilities. The Markov property of the BNs implies that all the probabilistic dependencies are graphically shown via arcs and that child nodes only depend on the parent nodes (Korb and Ann E. Nicholson, 2003).

In a previous paper, Barthelmes et al. (2017) explored the BN framework for modelling window control behaviour addressing 5 key questions: variable selection for identifying key drivers impacting window control behaviour; correlations between key variables; definition of the most suitable target variable; BN model with capabilities to treat mixed data; validation of a stochastic BN model. The proposed BN model was based on data collected in one residential apartment and included only physical and time-related factors as predictors

(Figure 10a). As a further step, the authors expressed the need for developing a more comprehensive model that includes a wider range of influential factors.

In this context, BNs permit to flexibly model complex relationships between diverse explanatory variables and window control behaviour by constructing a joint probability distribution over different combinations of the domain variables. Indeed, the BN model permits to easily model joint conditional dependencies of the entire set of variables through a graphical representation of the model structure (Korb and Ann E. Nicholson, 2003). The BN model also allows for structuring a variety of explanatory variables and multiple target variables in a hierarchical manner (Figure 10b). BNs are demonstrated to yield good prediction accuracy even with small datasets (Mylly Aki et al., 2002).

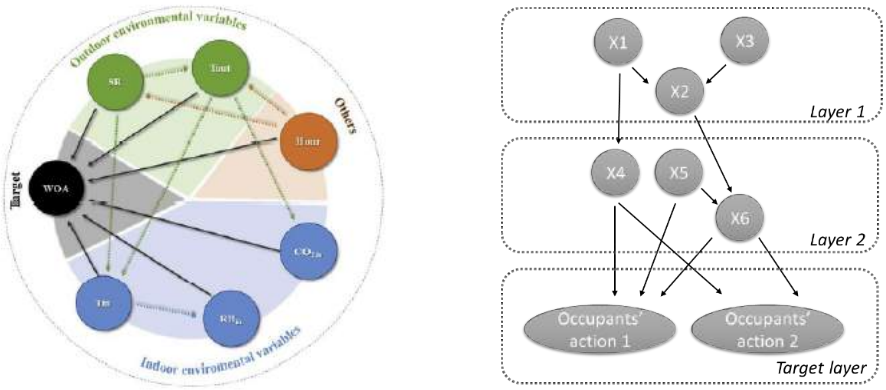


Figure 10. (a) left - BN model for window open action behaviour (WOA) by (Barthelmes et al., 2017), where the identified influencing factors are SR=Solar radiation, Tout=Outdoor temperature, Hour=Time of the day, CO2,in=Indoor CO_2 concentration, RHin=Indoor relative humidity, Tin= Indoor temperature), (b) right - Example of a multi-layered BN.

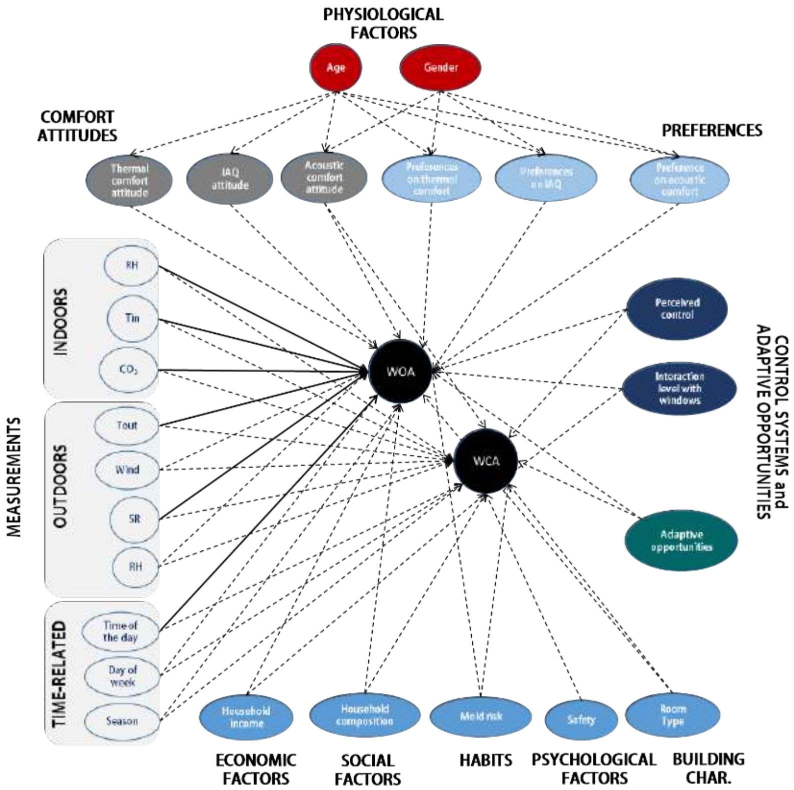


Figure 11. Preliminary proposal: Example of an extensive BN model for window control behaviour (WOA=window opening action, WCA=window closing action). Further investigation is needed for variable selection and definition of connection between variables.

Figure 11 shows a preliminary example of how the BN structure shown in Figure 10a could be extended to include a more extensive set of drivers and target variables. However, an extension of the model within the Bayesian Network framework addresses a set of challenges. In particular, in order to translate the theoretical model into an extended Bayesian network based on the current dataset, it is worth noting key challenges and aspects for the model construction.

- **Tailored variable selection:** To reduce the complexity of a final model, it is necessary to select a reduced set of key explanatory variables by means of a preliminary survey analysis or additional statistical analysis (e.g. Kolmogorov-Smirnov test). For example, the preliminary survey analysis showed that a number of variables could be excluded from the model, such as window control behaviour related to pets or smoking behaviour (almost all survey respondents did not report any habits related to these aspects). Also, further analysis on the relationship between influencing factors and aggregated window control behaviour data (e.g. total number of window openings/closings) might provide a first idea on important explanatory variables.
- **Data collection and definition of comfort attitudes:** In practice, it is challenging to collect survey-based information at finer time resolution as field measurements. In this case study, we collected survey-based information once at a specific time step during the heating period, while field measurements were collected in increments of minutes during a full year. It is therefore necessary to assume survey responses (e.g. comfort attitudes, preferences and habits) constant during the data collection period. Based on this assumption, we defined thermal comfort attitudes (TCA) by comparing thermal sensation votes at the time of response to the PMV calculated by standard EN15251 at the measured environmental conditions (Figures 12 and 13). Thermal comfort attitude will be added to the Bayesian Network to indicate individual differences between predicted and actual thermal comfort.

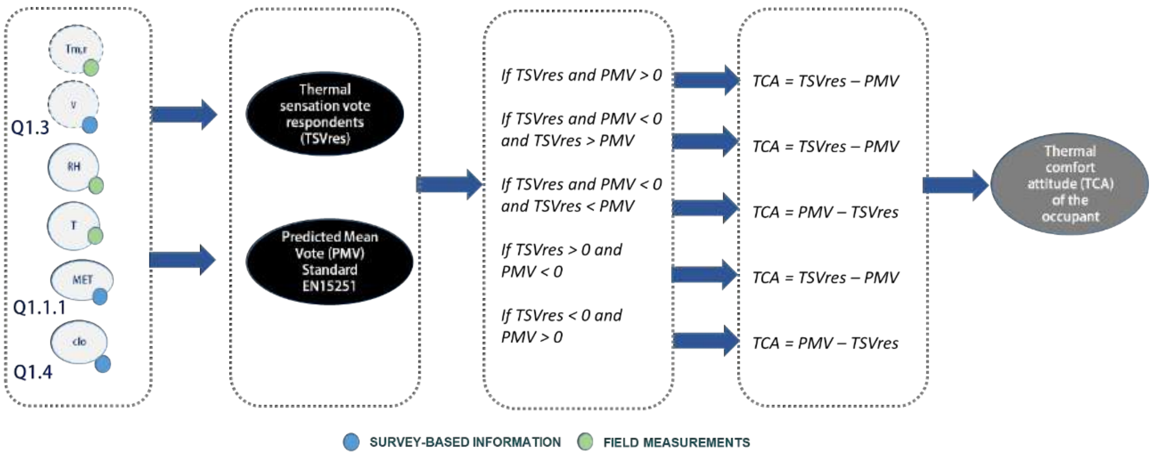


Figure 12. Example: Definition of thermal comfort attitudes based on measurements taken during the compilation of the survey and thermal sensation votes of the respondents.

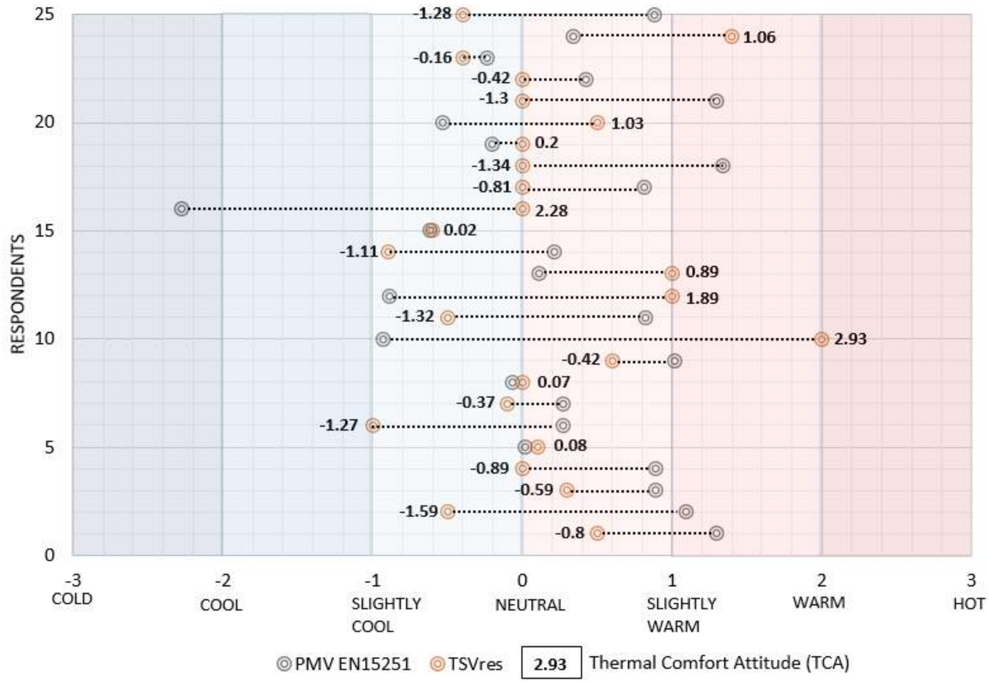


Figure 13. Application example: Definition of thermal comfort attitudes based on measurements taken during the compilation of the survey and thermal sensation votes of the respondents.

- **Definition of target variables**: In a previous study (Barthelmes et al., 2017) and in line with other studies (Andersen et al., 2013), it is highlighted that window control action is more suitable as a target variable to model window control behaviour than the window open/close state. Indoor environment variables such as indoor CO_2 concentration level and indoor temperature were identified as key variables that change the window state, but at the same time, the indoor environment conditions are directly influenced immediately after a window control action takes place. Hence, when the window state is used as a target variable, indoor environment variables as predictors may not correctly represent relationships between the indoor variables and window control behaviour. A next step is developing an extended Bayesian Network based on the proposed theoretical model with multiple target layers, such as window opening action (WOA) and window closing action (WCO). Further work to develop a comprehensive model for predicting major control actions (e.g., thermostat control, window blinds control or light switching) will depend on comprehensive monitoring campaigns that permit to collect data on a range of control actions altogether.
- **Connection between variables and parameter learning:** The connections and conditional dependencies/independencies between nodes should be carefully investigated. The conditional dependencies between different explanatory variables can be learned by machine learning algorithms (Margaritis et al., 2003) that extract information from the training dataset, but should always be accurately verified by experts, since automated learning processes often lead to random arc directions that may not represent real world phenomena. In addition, the treatment of mixed data needs to be carefully addressed for structuring a hierarchical BN model, since current modelling environments (e.g. bnlearn package for the R environment) are not suited to fully exploiting information embedded in the mixed dataset when continuous variables depend on discrete variables (Barthelmes et al., 2017). Hence, handling mixed data can become a tricky challenge when working

with more complex networks composed by a variety of variables of continuous and discrete nature. However, the capability of treating mixed data is crucial especially for the context of window control behaviour in which the main target variable is often binary (open/close) and explanatory variables are continuous. The proposed approach in the previous study is to create a bottom-up model in which the arcs are reversely connected from the discrete target variable to the continuous response variables. Future work is needed to investigate whether this proposed approach is feasible to structure a hierarchical BN model.

- **Model inference:** Once the model is trained, it is possible to infer the model and ask questions about the nature of the data. In particular, this step permits to carry out predictive analysis, diagnostic analysis and the investigation on relationships and conditional dependencies between individual nodes of the network. In our case study, BNs allows for understanding relationships between explanatory variables and window control behaviour and for predicting window control behaviour given certain environmental conditions, but also individual preferences and characteristics of the occupants.

5. Conclusion

In this paper, we developed a theoretical multi-layered model of occupant's window control behaviour with an extensive set of drivers based on field measurements and information collected through a tailored survey framework in Danish Dwellings. The survey structure was developed for collecting detailed individual characteristics of the occupants regarding: (1) individual comfort attitudes and preferences, (2) physiological factors and individual characteristics (e.g. gender, age, height, weight, smoking habits), (3) social factors (e.g. education, household composition, household income), (4) perceived control and psychological factors (e.g. satisfaction of control options, knowledge of control options, interaction frequency with controls, safety), (5) motivations and habits related to window control behaviour, and (6) adaptive opportunities (e.g. sequence of actions that occupants perform when they feel hot/cold). Further work is necessary to implement a tailored theoretical model within the Bayesian Network framework, which represents a promising modelling environment that can capture probabilistic dependencies between energy-related actions of the occupants with building envelope and systems, and an extensive set of driving factors. However, it is necessary to carefully address challenges that come with modelling complex datasets within the BN framework, especially given the limitations of current modelling environments to handle mixed data. Future work should also include other control opportunities in the same model, such as thermostat control, window blinds control or light switching.

6. Acknowledgements

This research was part of the UserTEC project (User Practices, Technologies and Residential Energy Consumption) (www.sbi.dk/usertec), which was financed by Innovation Fond Denmark.

7. References

Ajzen, I. and Madden, T. J., 1986. Prediction of goal-directed behavior: Attitudes, intentions, and perceived behavioral control. Journal of Experimental Social Psychology, 22(5), pp 453–474

Andersen, R., Fabi, V., Toftum J., Corgnati, S.P., Olesen B., 2013. Window opening behaviour modelled from measurements in Danish dwellings. Building and Environment, 69, pp 101–113

Andersen, R.K., Fabi, V., Corgnati, S. P., 2016. Predicted and actual indoor environmental quality: Verification of occupants' behaviour models in residential buildings. Energy and Buildings, 127, pp 105–115

Andersen, R. V., Olesen, B. and Toftum, J., 2007. Simulation of the Effects of Occupant Behaviour on Indoor Climate and Energy Consumption. Clima 2007 WellBeing Indoors, Helsinki, Finland, 10 - 14 June 2007.

Barthelmes, V. M., Heo, Y., Fabi, V., Corgnati, S.P., 2017. Exploration of the Bayesian Network framework for modelling window control behaviour. Building and Environment, 126, pp 318–330

Borgeson, S. and Brager, G., 2008. Occupant Control of Windows: Account for Human Behavior in Building Simulation. Internal report October 2008, Center for the Built Environment (CBE). Available from: https://escholarship.org/uc/item/5gx2n1zz

Calì, D., Andersen, R.K., Müller, D., Olesen, B., 2016. Analysis of occupants' behavior related to the use of windows in German households. Building and Environment, 103, pp 54–69

Cen (European Committee for Standardization, 2007). EN 15251 Standard. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels: European Committee for Standardization; 2007.

Chatterton, T., and Department of Energy and Climate Change, 2011. An introduction to Thinking about "Energy Behaviour": a Multi Model Approach. Department of Energy and Climate Change website. Available from: http://eprints.uwe.ac.uk/17873

D'Oca, S., Chen, C., Hong, T., Belafi, Z., 2017. Synthesizing building physics with social psychology: An interdisciplinary framework for context and occupant behavior in office buildings, Energy Research and Social Science, 34, pp 240–251

Fabi, V., Andersen, R.V., Corgnati, S.P., Olesen, B.W., 2012. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. Building and Environment, 58, pp 188–198

Fabi, V., Andersen, R. K., Corgnati, S., 2015. Verification of stochastic behavioural models of occupants' interactions with windows in residential buildings. Building and Environment, 94, pp 371–383

Fanger, P. O., 1973. Assessment of man's thermal comfort in practice. Occupational and Environmental Medicine, 30(4), pp 313–324

Haldi, F. and Robinson, D., 2008. A comparison of alternative approaches for the modelling of window opening and closing behaviour. Air Conditioning and the Low Carbon Cooling Challenge Conference, Windsor, United Kingdom, 27 -29 July 2008.

Haldi, F. and Robinson, D., 2009. Interactions with window openings by office occupants. Building and Environment, 44(12), pp 2378–2395

Indraganti, M. and Rao, K. D., 2010. Effect of age, gender, economic group and tenure on thermal comfort: A field study in residential buildings in hot and dry climate with seasonal variations. Energy and Buildings, 42(3), pp 273–281

Kingma, B. and Van Marken Lichtenbelt, W., 2015. Energy consumption in buildings and female thermal demand, Nature Climate Change, 5(12), pp 1054–1056

Korb, K. B. and Ann E. Nicholson, 2003. Introducing Bayesian Networks. Bayesian artificial intelligence, pp 29–54

Margaritis, D., 2003. Learning Bayesian Network Model Structure from Data. PhD. Carnegie Mellon University.

Masoso, O. T. and Grobler, L. J., 2010. The dark side of occupants' behaviour on building energy use. Energy and Buildings, 42(2), pp 173–177

Mulville, M., Jones, K., Huebner, G., Powell-Greig, J., 2017). Energy-saving occupant behaviours in offices: change strategies. Building Research and Information, 45(8), pp 861–874

Mylly Aki, P., Silander, T., Tirri, H., Uronen, P., 2002. B-COURSE: A WEB-BASED TOOL FOR BAYESIAN AND CAUSAL DATA ANALYSIS. International Journal on Artificial Intelligence Tools, 11(3), pp 369–387

Paciuk, M., 1990. The Role of Personal control of the Environment in Thermal Comfort and Satisfaction at the Workplace. 21th Annual Conference of the Environmental Design Research Association, pp 303–312

Pfafferott, J. and Herkel, S., 2007. Statistical simulation of user behaviour in low-energy office buildings. Solar Energy, 81(5), pp 676–682

Rijal, H. B., Tuohy, P., Nicol, F., Humphreys, M.A., Samuel, A., Clarke, J., 2008. Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings. Journal of Building Engineering, 1(1), pp 17–30

Schweiker, M., Haldi, F., Shukuya, M., Robinson, D., 2012. Verification of stochastic models of window opening behaviour for residential buildings, Journal of Building Performance Simulation, 5, pp 55–74

Schweiker, M., 2017. Understanding Occupants' Behaviour for Energy Efficiency in Buildings. Current Sustainable/Renewable Energy Reports, pp. 1–7

Schweiker, M. and Shukuya, M., 2009. Comparison of theoretical and statistical models of air-conditioning-unit usage behaviour in a residential setting under Japanese climatic conditions. Building and Environment, 44(10), pp 2137–2149

Toftum, J., 2010. Central automatic control or distributed occupant control for better indoor environment quality in the future. Building and Environment, 45(1), pp 23–28

Warren, P. R. and Parkins, L. M., 1984. Window-opening behaviour in office buildings. Building Services Engineering Research and Technology, 5(3), pp 89–101

Wei, S., Jones, R. and De Wilde, P., 2014. Driving factors for occupant-controlled space heating in residential buildings. Energy and Buildings, 70, pp. 36–44

Yun, G. Y. and Steemers, K., 2008. Time-dependent occupant behaviour models of window control in summer. Building and Environment, 43(9), pp 1471–1482

Zhang, Y. and Barrett, P., 2012. Factors influencing the occupants' window opening behaviour in a naturally ventilated office building. Building and Environment, 50, pp 125–134

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Regression Dilution, Bayesian Analysis and Adaptive Thermal Comfort

Harry R. Kennard[1], David Shipworth[1], Gesche Huebner[1], J. Fergus Nicol[1],

[1] Energy Institute, University College London, UK. harry.kennard.13@ucl.ac.uk

Abstract: The adaptive approach, as realised in adaptive thermal comfort standards, is an empirically based estimation of the gradient of an ordinary least squares (OLS) linear regression model of operative temperature at neutral comfort vote (the neutral temperature), and external temperature. The neutral temperature itself may be determined by an OLS regression of comfort votes against operative temperature. Thus the strength of the adaptive model's relationship rests on the estimation of two regression gradients. Correct estimation of these gradients is therefore essential in correct implementation of adaptive standards. Should these independent variables be measured with error, the gradient of the regression will be systematically underestimated, in a phenomenon known as regression dilution. This paper uses a Bayesian method which is not effected by regression dilution to reanalyse SCATs data for thermal comfort in free-running UK offices. Following a discussion of the probable uncertainties present in the variables that underpin adaptive thermal comfort standard EN15251, the broader implications of regression dilution are outlined. Application of this approach serves to highlight the importance of conceptual clarity and specification of the measureands of operative temperature and external temperature on which the gradient of the regression slope of the adaptive relationship is critically dependent.

Keywords: Adaptive thermal comfort, Regression dilution, Bayesian analysis.

1. Outline

The adaptive thermal comfort model has become accepted and standardised in Europe through EN 15251. The underlying data used in the development of this standard was that collected in the SCATs (Smart Controls and Thermal Comfort) project funded by the European Commission, Joule III programme (Nicol and McCartney 2000, Nicol and Humphreys 2010). The method of analysis of the data from which the strength of the adaptive relationship is drawn makes extensive use of linear regression. As noted in Humphreys et al. (2016), in cases where the independent variable is measured with error, the estimate of the regression gradient can be systematically underestimated. An examination of the potential sources of error and uncertainty is given in the next section. In the remainder of this paper a Bayesian approach to linear fitting is introduced, and a reanalysis of example data from free running UK buildings taken from the SCATs database presented to demonstrate it. Finally, the wider implications of this approach are considered.

2. The adaptive approach

One core aspect of the adaptive approach to thermal comfort is to relate the temperature which building users find comfortable to external temperature. Humphreys et al. (2016, p.284) outline the various processes which determine this relationship within EN 15251. While this example is drawn from the data and work in establishing this standard – the limitations identified are transferable to any adaptive thermal comfort standard – or indeed any process relying on Ordinary Least Squares (OLS) regression.

The process for determining the relationship between thermal comfort and external temperature occurs in two distinct stages. First, thermal comfort survey data (section 2.1) is collected and an average neutral[1] temperature determined for the survey, which usually relates to a particular building. The average neutral temperature can be determined either using a regression of indoor temperature, usually specifically operative temperature, against the comfort votes of the participants, or by fixing a thermal sensitivity (the Griffiths method) and extrapolating a neutral temperature from the mean comfort vote and mean internal (operative) temperature. This is discussed further in section 5.

The second stage is to produce a regression of external temperature, either an average or moving average, against the mean comfort vote for that building. Since both processes involve regression, we examine each in turn to discuss possible sources of error.

2.1. Comfort votes against operative temperatures measured in field trials

In this section, the variables and sources of uncertainty in the first stage of the adaptive approach are considered.

2.1.1 Variables

The key variables measured in field trials are the participants' assessment of their level of comfort, which are typically recorded on an ordinal scale, and a temperature recording which aims to capture their immediate thermal environment such as the operative temperature (Nicol et al., 2012) as recorded by a globe thermometer.

2.1.2 Sources of uncertainty

There are a wide variety of sources of uncertainty involved in the determination of thermal sensation – and comparatively little work done on trying to quantify the extent of this uncertainty. Recent work by Schweiker et al. (2016) has shown that the underlying assumption implicit in the application of parametric measures of analysis (including OLS regression) – that the scale can be treated as interval rather than ordinal – do not apply to thermal sensation scales. We do not address the implications of such sources of uncertainty in this paper, and assume that it is possible to model them as Gaussian. The focus of this paper is on assessing the extent to which errors in the measurement of thermal sensation arising from instrument error (instrument reliability); and from underspecification of the measureand (imprecision in the definition of what is being measured), introduce errors into the independent variable that give rise to biases in estimates of the regression coefficient.

There have been various attempts to quantify the measurement error in thermal comfort scales. Previous papers (Shipworth et al., 2016) have applied the true score theory framework to thermal comfort scales. This asserts that the observed score 'X' equals the true score 'T' plus random error 'e' giving: $X = T + e$. The error term 'e' is itself composed into two elements: random error 'e_r', and systematic error 'e_s' giving: $X = T + e_r + e_s$. When studying variance in a measured dataset, this is then expressed as: $var(X) = var(T) + var(e_r) + e_s$. Here random errors manifest in an increase in the '$var(e_r)$' term, and systematic errors manifest in the 'e_s' introducing a bias into data moving the observed values away from the true value of their mean. Any form of analysis seeking to explain the variance in the population 'var(T)' assessed through measurement of the sample from that population 'var(X)', needs to distinguish between the true underlying variance in population 'var(T)' and measurement errors '$var(e_r)$'. When considering the SCATs data, we therefore know that some of the observed scatter will be because of measurement error '$var(e_r)$'. It is this component of the scatter that gives rise to regression dilution.

[1] The neutral temperature is often referred to as the comfort temperature, but the former is used here to avoid confusion with the central three votes used in ASHRAE scales.

In measurement theory terms, measurement error is closely related to measurement reliability. “A measure that has no random error (i.e., is all true score) is perfectly reliable; a measure that has no true score (i.e., is all random error) has zero reliability.” (Trochim et al., 2016). Shipworth et al. (2016) report three previous attempts to quantify thermal comfort scale reliability using a variety of different methods.

Lundgren et al. (2014) used test-retest reliability methods to assess the reliability of their Cold Discomfort Scale (CDS). They determined a weighted kappa coefficient - a within-subjects measure of correlation between the test and retest scores. Instrument reliability was 85% - leaving an unexplained within-subject variation of 15%.

Khogare et al. (2011) applied the split-half method to assess reliability of their thermal satisfaction scale. The correlation between the halves was 0.8. Applying the Spearman-Brown prophecy formula they derived a full test reliability of 88% - leaving an unexplained within-subject variation of 12%.

Dehghan et al. (2015) applied a generalized version of the split-half method called Cronbach’s alpha to their ‘Heat Strain Score Index’ (HSSI) to assess scale reliability. They also evaluated content validity, structure validity, concurrent validity and construct validity. Their final 21-item scale had a reliability of 91% - leaving an unexplained variance of 9%.

With respect to the measurement of globe temperature a number of issues arise. The most easily quantifiable is the precision of globe thermometers. The SCATs fieldwork used grey sphere globe thermometers, and while no value is available in the SCATs final report (Wilson et al, 2000) the precision of such devices could be high, of the order ±0.1K[2]. Moreover, the SCATs globe temperature data are recorded to 2 decimal places, which is potentially suggestive of high precision. Of greater impact than instrument precision are issues of underspecification of the measurand. Instructions on placing globe thermometers in field trials follow the ‘right here right now’ principle of measuring as close to the participant in time and space as possible. Even applying this principle, both the radiative and air temperature to which different parts of individuals seated at desks are exposed is likely to differ from a globe thermometer placed adjacent to them. Evidence suggests that occupants are differentially sensitive to air and radiant temperature in different parts of their bodies – an issue exacerbated by the different thermal environments above and below desk height in office workstations. Another consideration is the time the globe takes to settle and leaving enough time for this to happen when visiting a number of subjects in a building.

Quantifying the uncertainty that arises between globe temperature measurement methods and model assumptions, and the ‘true’ experienced temperature of occupants, would require a substantial body of primary experimental empirical research. For the purposes of this paper we have made simplifying assumptions for the purposes of assessing the sensitivity of adaptive thermal comfort regression models to uncertainties in the explanatory variables (see Table 1 below).

2.2. Mean operative temperature at neutral comfort, and the ‘external’ temperature.

The only new variable introduced at the second stage of the process is the external temperature – this is used in a regression against mean neutral temperature. Estimation of the uncertainty in measurement of the external temperature is challenging as adaptive

[2] This figure is derived from an accuracy estimate reported in the SCATs documentation cited above; “the Swedish National Testing and Research Institute found that the Globe temperature was found to be reading 0.2- 0.3^{o}C below the standard at temperatures at a variety of air-radiant temperature combinations.”. The precision of this systematic offset informs the above estimate.

thermal comfort theory does not make explicit which external temperature occupants adapt to. It is often assumed that they adapt to the external temperature of the building they occupy. Practically, the air temperature recorded at the nearest weather station is used if local measurements are not available. However, there is no explicit theoretical justification as to why it is this external temperature that would drive occupant adaptive behaviour. It is plausible that it may be the temperature at their place of residence which influences how they dress in the morning, or the forecast daily maximum temperature for their place of work, or the experienced temperature during parts of their commute. In fact the multiple mechanisms of thermal adaptation may be driven by different external temperatures for different people and may vary over time. In practice, a heuristic approach to the definition of external temperature is used which has settled on the use of a running mean, T_{rm}, defined as

$$T_{rm} = (1-\alpha)\{T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} + \cdots\},$$

where α is a constant with a value between 0 and 1 which determines the extent to which previous days contribute to the running mean, and T_{od} is the 24 hour daily mean temperatures for the previous days. The value of α used in EN15251 is 0.8, and was chosen as to maximise the correlation with the indoor neutral temperature (Nicol et al., 2000, 2010). Instrumental uncertainty in external temperature averages is likely to be less than 0.5K – one Met Office estimate of the uncertainty in daily gridded temperature averages is 0.94 K (2009). A study into the spatial variation in air temperature by Smith et al. (2011) in Manchester presents a complex picture, in which daytime average temperature differences between urban and rural areas of the same conurbation are as much as 3K. The extent to which an individual weather station represents the local environment therefore depends to a great extent on the local environment's heterogeneity.

Table 1. A summary of the different estimates which contribute to the range of values used in the sensitivity analysis in section 4.

Variable	Uncertainty estimate	Comment
Thermal sensitivity scale reliability (T_f)	**15%** **12%** **9%**	**Lundgren et al. (2014)** **Khogare et al. (2011)** **Dehghan et al. (2015)**
Globe temperature instrument imprecision (T_g)	**0.1 K**	**Estimate based on Wilson et al. (2000)**
Operative temperature underspecification of the measurand	**0.5 K**	**Smart Controls and Thermal Comfort Project. Final Report – Task 1 – Instrumentation (Wilson et al., 2000)**
External temperature instrument imprecision	**0.94 K**	**Met Office (2009). (N.B. this figure refers to the daily average from gridded data set temperatures.)**
External temperature underspecification of the measurand	**>1K**	**Smith et al. (2011)**

3. Regression dilution

The ordinary least squares (OLS) method of fitting a line to data is one of the most widely used in science. In its most simple form, it is the process that estimates the gradient and intercept of a linear relationship between independent and dependent variables by minimising the sum of the squared deviations between the data and the line (see figure 1). The use of OLS depends upon several assumptions about the data that should, if properly applied, restrict its usage. Most importantly here is the requirement that the independent variable should be measured without error. If it is not, the result is a systematic bias of the estimated gradient towards zero, known as "regression dilution" or "attenuation bias" (Spearman, 1904). The following section examines this effect, and outlines an alternative method involving elements of Bayesian analysis that is not effected by regression dilution. This topic is extensively covered by Humphreys et al. (2016), but some aspects are reviewed here, and a different emphasis made.

The consideration of error in least-square fits of linear relationships is not new. As early at 1878, Kumell gave the topic consideration. Over the years, the topic has been considered, forgotten, rediscovered and reconsidered on several occasions, and typically not presented as a complete framework. This is partly due to slight variations in the requirements of each field, but probably more a question of intellectual pragmatism: simple least squares is generally considered good enough for most applications. There is a degree of truth to this, careful consideration of errors does not usually result in order of magnitude differences to results, although the difference it makes can be significant in many instances. Typically, the effect is greatest in fields that produce precise estimates based on limited or error prone data; econometrics, for example, makes extensive of variables which are measured with error (Hausman, 2001).

3.1. Least squares regression

Before moving onto the specifics of the approach undertaken here, it is helpful to briefly review some aspects of least squares curve fitting. For 'ordinary' (i.e. unweighted) least squares fitting the gradient of the line of *best* fit is given by

$$\beta = \frac{\mathrm{c(x,y)}}{v(x)} \tag{1}$$

where c(x,y) is the covariance[3] of x and y, and v(x) the variance[4] of x. This equation is the result of a procedure to minimise the sum the vertical deviations between the regression line and data. It is noteworthy that this equation does not depend of the variance of y, which indicates that estimates of the gradient using OLS are not effected by normally distributed measurement errors in y. The derivation of the equation 1 result is given in Rao (1973).

Figure 1 compares three approaches to least squares fitting. In panel A, the standard OLS approach is shown, for which the sum of the squares of the vertical deviations from the regression line are minimised. Panel B illustrates the result of minimising the sum of the squares of the orthogonal distances between the data and the regression line (see section 3.2 below for further discussion). Finally, panel c shows the same data again, but this time with the horizontal deviations considered, and a reversed regression given for which it is assumed the errors on the dependent variable is zero. The forward regression gradient (m) and reverse (m') value are related by ${}^{m}/_{m'} = R^2$. This means that data with low R^2 values, i.e. data which are highly scattered about the line, have the greatest potential to be impacted by regression dilution.

[3] $\mathrm{c(x,y) = E[(x - E[x])(y - E[y])]}$ where E[x] is the expectation value of x
[4] $\mathrm{v(x) = E[(x - E[x])^2]}$

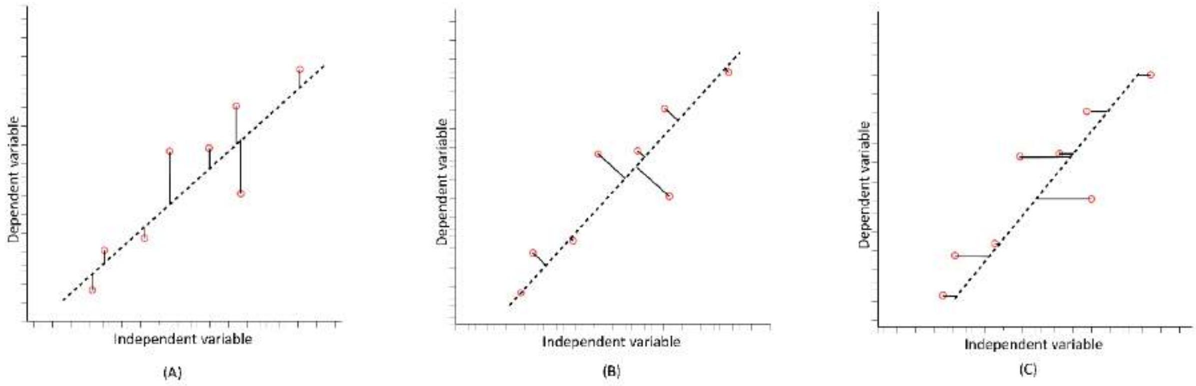


Figure 1: A) The vertical deviations from the regression line which are minimised under standard OLS. B) The result of minimising the sum of squares of orthogonal distances C) The reverse regression of y on x, which assumes that all the error is present on the independent variable; this means the horizontal distances should be minimised.

3.2. Methods for correcting for regression dilution

Broadly speaking, two classes of methods exist for dealing with regression dilution. The first, less preferable approach, is to *correct* the estimate given by OLS, in order to reverse the effects of regression dilution. This approach is adopted by Cheng and Van Ness (1999) in a general statistics context, and specifically to thermal comfort by Humphreys et al. (2016). The correction factor depends on the degree of error in the independent variable and multiplies the OLS estimate of the gradient. However, the process of applying a correction factor is not preferable as, in certain instances, there is risk of overcorrection (Smith et al. 1996) and using a regression model that has criteria which are known not be satisfied by the data is somewhat dissatisfying from the outset.

The second approach is to build knowledge of error in the dependent variables into the regression model, the 'errors in variables' approach (Fuller, 1987). One simple example of this approach has become known as Demming regression (Demming, 1943) and is appropriate when the ratio of the errors of the variables is known. The approach is not to minimise the vertical differences between the data and the regression line, but a distance determined by the ratio of the errors on the variables involved in the regression. If all the error occurs in the independent variable, then the horizontal distances are minimised (figure 1(C)). The case for equal error, and hence orthogonal distances[5], is shown in figure 1(B). The geometric basis of the Bayesian method described by Hogg et al. (2013) which is discussed in the following section and applied to thermal comfort data from the SCATS database is an analogue to the Demming approach.

It should be noted, the case where all the error occurs on the independent variable is equivalent to an OLS regression with the variables reversed, and represents an upper limit on the gradient (for positively sloped data). Equivalently, the standard OLS regression procedure, in which all the error is assumed to be in the dependent variable, gives a lower limit of a the gradient. Humphreys et al. (2016, p.226) illustrate this point and suggest that the geometric mean of the two limiting cases "might better represent the relation between the room temperature and the subjective warmth than would either of the two regression lines".

[5] The orthogonal case originally appears in Adcock (1878).

However, Hogg et al. (2013) provide justification of why this should never be done. This point is addressed further in section 5

3.3. A Bayesian approach for straight line fitting

Bayesian approaches to data analysis (Sivia, 2006) are in wide use alongside 'frequentist' approaches, and there is extensive debate surrounding their appropriate use and philosophical basis (Vallverdu, 2015). Bayesian analysis allows for the inclusion of prior information about variables into the analysis and permits direct model comparison, by examining the relative probability that a model is supported by a particular dataset. It also has the advantage that error estimates automatically result from the computation of the probability distribution for each variable. Indeed, unlike frequentist approaches, which assume parameters such as the slope of a regression line have fixed values that are determined through multiple repeat measurements, parameters in Bayesian analysis are probability densities which evolve as additional information is provided – measures of the spread of these probability densities give an indication of the confidence that can be attributed to the result. D'Agostini (2005) provides an in-depth discussion of the process of fitting data that has error on both dependent and independent variables. In the specific case of the linear fit, an approach developed and coded in Python by Hogg et al. (2013) and Foreman-Mackay et al. (2013) is adapted in the following analysis[6].

3.3.1 Model description

The model uses labels x and y for the independent and dependent variables respectively; in section 4 these will be the variables considered in section 2.1, namely operative temperature and comfort vote. For a set of measurements (x_i, y_i) it is assumed there is an underlying linear function which relates them of the form

$$y = mx + b$$

with known Gaussian error (σ_x^2, σ_y^2) on each measurement for both variables, respectively, unlike OLS which assumes no error in x. This model is equivalent to the described in section 2.1.1. This can be visualised as a generalisation of an error bar, forming a 2D ellipse surrounding each measurement point.

The Python program used here computes three sets of estimates for m and b, the first two using standard statistical methods, and the third using a Bayesian approach, as follows.

1) *OLS estimate of m and b:* Both the standard OLS regression of x on y and the reverse regression of y on x. These two estimates give upper and lower bounds on m and b, as described in section 3.1.

2) *Maximum likelihood estimate of m and b:* The equation for this is given in appendix 2. It is derived in Hogg et al. (2013), and calculated in the Python program using a standard Python algorithm.

3) *Monte Carlo Markov Chain (MCMC) estimate of m and b:* This estimate is the Bayesian aspect of the analysis. In general MCMC algorithms sample from probability distributions. In this specific instance it is the posterior probability distribution, i.e. the combination of parameters m and b which best accord with the data and the prior information supplied (Foreman-Mackay et al. 2013). Error estimates on m and b result automatically from computing this probability distribution. Again, the reader is directed to Hogg et al. (2013) for a more technical discussion of this calculation.

---

[6] An instructive example is given by Foreman-Mackay at dfm.io/emcee/current/user/line [accessed 28.2.2018]

Finally, it should be noted that for situations in which there is no error in the x variable (i.e. $\sigma_x^2 = 0$) the results are identical to OLS regression.

4. An example: free running UK offices

The SCATs database underpins adaptive thermal comfort standard EN 15251. The study involved taking monthly surveys in European offices of occupants thermal comfort assessment on a 7 point ASHRAE scale. As laid out by Humphreys et al. (2016, p.302), the neutral temperature for the SCATS data "was taken to be the operative temperature at which the respondent would have recorded thermal neutrality had the divisions on the ASHRAE scale corresponded to a change in operative temperature of 2K". This is equivalent to fixing the gradient used in the Griffiths method at 0.5 votes/K (Nicol et al., 2010). The following analysis examines this gradient (m) using the approach outlined above and so for clarity values of the intercept (b) are omitted.

As discussed in section 2, it is difficult to calculate the measurement errors on the variables involved in the regression of operative temperature against comfort vote. Therefore, the analysis is repeated for different plausible values of the error in operative temperature and comfort vote. The operative temperature error, σ_x^2, takes 3 values: 0.5, 1.0 and 2.0 and the comfort vote error σ_y^2 takes values 3 values[7]: 0.35, 0.53 and 0.88. Together these form nine possible combinations of error on each of the variables. Moreover, it is assumed the error on each individual data point is the same, i.e. there is homogeneity in the errors across the dataset as a whole.

The computation of the regression lines was then undertaken using a number of modified Python scripts developed originally by Foreman-Mackay, Hogg, Bovey and Lang using these values. The priors for both m and b were chosen to be uninformative, to reflect the fact that there is no initial preference for their values, other than extreme values being disallowed[8].

The R^2 value for this data is low, at 0.156. This means the regression is particularly susceptible to regression dilution. The standard OLS estimate for m for this data is 0.35. The reverse regression of y on x gives 2.24. As outlined in section 3.1 the ratio of these values (0.35/2.24) is equal to the R^2 value.

Figure 2 shows the results for the maximum likelihood estimate alongside the OLS estimate for error estimate $(\sigma_x^2, \sigma_y^2) = (0.5, 0.88)$. Ellipses help visualise the estimate of error surrounding each survey measurement. This can be contrasted with figure 3 which shows the effect of an error combination which results in a much higher estimate for the gradient than the OLS estimate. For this figure the errors take values $(\sigma_x^2, \sigma_y^2) = (2.0, 0.35)$. It should be noted that both figures 2 and 3 show regression lines which are bounded by the standard OLS estimate (m = 0.44) and the reverse OLS estimate of Y on X (m = 2.25). These limits are important for the discussion given in section 5.

[7] The slightly artificial values for the range of reasonable values for the error on the comfort vote arise from taking a percentage of the whole scale range (i.e. 7). The extent to which ordinal variables are approximated by nominal variables with Gaussian error is discussed by Schweiker et al (2016).

[8] Specifically, the prior is zero if $-20 < m < 20$ and $-300 < b < 300$.

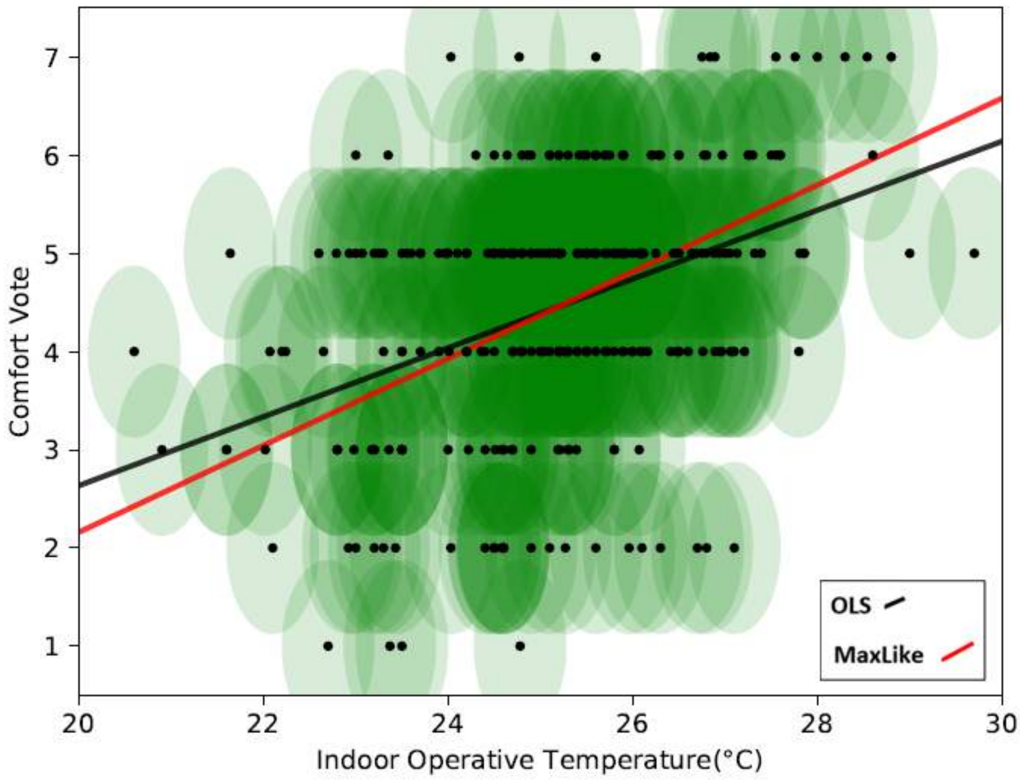


Figure 2. The maximum likelihood estimate (red line) for the gradient (m = 0.44) and error ellipses (c.f. figure 4) for each data point shown in green. The OLS estimate for the relationship between indoor operative temperature and comfort vote, from the SCATS database (m = 0.35), with the error on x and y at 0.5 and 0.88 respectively the MCMC estimate for m is 0.44±0.04.

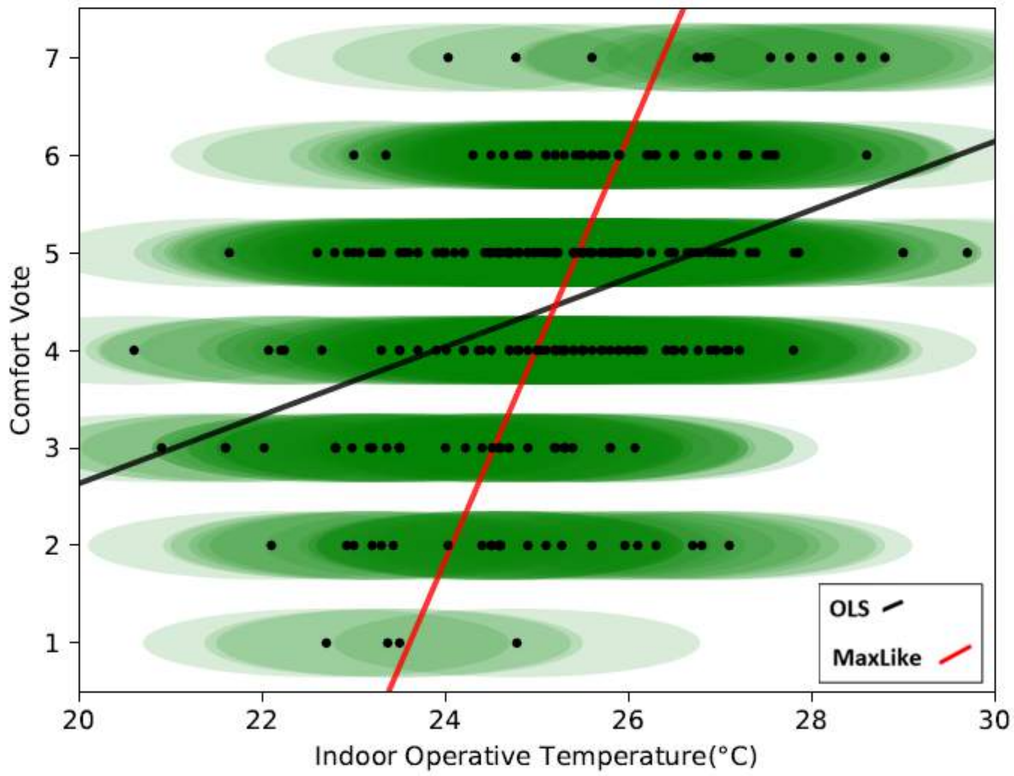


Figure 3. The regression gradient for the error on x and y with values 2.0 and 0.35 respectively is 2.17, much higher than the case shown in figure 2. The error ellipses are again shown in green. This demonstrates that under different error assumptions the gradient is very different.

The different values of m which result from the complete range of estimates for the error on indoor operative temperature and comfort vote are given below in table 2. When the error on the independent variable is high relative to the dependent variable, the gradient is several times higher than the OLS estimate. Crucially, the majority of these estimates are higher than the 0.5 votes/K assumed by Nicol et al (2000, 2010).

Table 2. A summary of the different regression gradients as given by the maximum likelihood estimate, in units of votes/K, which result from various values of the error on Tg, the indoor operative temperature and Tf the comfort vote.

		Error T_g		
		0.5	**1.0**	**2.0**
Error T_f	**0.35**	**1.24**	**1.96**	**2.17**
	0.53	**0.69**	**1.66**	**2.08**
	0.88	**0.44**	**0.91**	**1.81**

The use of MCMC allows straightforward computation of uncertainty on the estimates for m. By way of example, and making use of upper and lower indices to denote the range of ±1 standard deviation, the MCMC estimate of the diagonal values from table 2 of m at particular σ_x^2 and σ_y^2 [denoted m(σ_x^2, σ_y^2)] are as follows:

$$m(0.5,0.35) = 1.25^{0.06}_{-0.05}$$
$$m(1.0,0.54) = 1.67^{0.17}_{-0.14}$$
$$m(2.0,0.88) = 2.05^{0.60}_{-0.38}$$

Generally, as the uncertainty on each of the variables increases so too does the uncertainty on the estimate of m. All of these estimates lie well outside the OLS estimate of the gradient (m=0.35) and demonstrate the sensitivity of the estimate of m to the particular values of σ_x^2 and σ_y^2 which are used.

5. Discussion

The analysis in the previous section demonstrates the great impact that different error estimates can have on the gradient of a regression line of operative temperature vs comfort vote. However, the extent to which the potential underestimation of the regression gradient between internal (operative) temperature and comfort vote affects the estimate of the relationship between external temperature and neutral temperature depends on the process that determines the neutral temperature itself. As Humphreys et al. (2016) explain the neutral temperature may simply be the point of intercept between the regression line and the neutral comfort vote value. Under this approach, it is possible to estimate the maximum impact of an underestimate of the gradient for the SCATS example above.

The highest possible value for the regression gradient is given by the *reversed* y on x regression. The difference neutral temperature derived using this regression line (T_c') and the neutral temperature derived from the standard x on y forward regression T_c' is given by this simple relationship, derived in Appendix 1.

$$T_c' - T_c = \frac{1}{m}(1 - R^2)(\overline{y} - k)$$

where m is the gradient of the standard forward regression line, R^2 the coefficient of determination, $\overline{y}$ the average comfort vote and k the neutral comfort vote value. In the case of the example from the SCATS data on free running UK buildings, discussed in the previous section, $T_c' - T_c \approx 1$°C. Somewhat paradoxically, if this difference is interpreted as an uncertainty on T_c, the potential impact of regression dilution in the subsequent regression of external temperature on T_c may in fact be reduced. Increasing the uncertainty in the dependent variable (in this case T_c) serves to make the standard OLS approach more valid.

However, the neutral temperature is not always determined using the above method. The Griffiths method (Humphrey's et al., 2016)) effectively fixes the gradient by which the neutral temperature is determined, and extrapolates it from the means of the comfort vote and indoor (operative) temperature. Humphreys et al. (2016) suggest the impact of different choices of regression under the Griffiths method is small. Indeed, the value of the gradient tends to play less of role when the votes are close to the neutral temperature. Since Bayesian analysis allows the inclusion of prior information, the impact of selecting a sensitivity of 0.4/K verses 0.5/K, for example, could be quantified and compared to the method of intercept. This would involve a large amount of work, and in practice the impact is likely to be minimal.

5.1 Concluding remarks

This paper has demonstrated the application of a data analysis technique to quantify the different regression gradients that result from different assumptions about the errors underlying the variables in the adaptive approach to thermal comfort. While the quantification of the various errors in the adaptive approach's variables is challenging, the characteristics of this analysis show that the regression gradients involved in the adaptive approach are sensitive to these values. Counterintuitively, an increased uncertainty in neutral temperature may diminish the impact of uncertainties in external temperature.

One of the central assumptions in the above analysis was that the relationship between operative temperature and comfort vote really is described by a straight line. From this assumption it was demonstrated that the gradient of such a line is highly sensitive to the measurement error that can be attributed to each variable. However, it is clearly not the case that comfort vote is determined by a single variable, the operative temperature, let alone one which follows a simple linear relationship. Many other factors, such as air movement and humidity, as well as more difficult to measure aspects like clothing and metabolic activity levels are also clearly relevant. Assumptions about whether comfort vote can be described as a nominal variable with Gaussian error are also open to critique. The adaptive approach as a whole acknowledges the complex feedback mechanisms at play which impact thermal comfort which are not reducible to simple linear relationships.

However, it is also the case that multiple ordinary least square straight line fits underpin the realisation of the adaptive approach in adaptive thermal comfort standards, such as EN 15251. In this sense there is tension between making use of OLS fits as a convenient tool for capturing relationships on the one hand, and impact of the misapplication of them as demonstrated above on the other. The extent to which gradients in EN 15251 and other standards would change if re-analysed subject to the consideration of errors in the independent variable is the subject of a much longer program of study.

6. Appendix 1

In the case where the Griffiths method is not used, neutral temperature is the temperature that corresponds to neutral on the comfort scale, according to the regression line. The limits of the possible regression lines are defined by the OLS in the first instance, and then a similar process but with x and y are interchanged. This follows from assuming all of the measurement and other errors fall on the independent variable, and none on the dependent variable.

Following this, the gradient and intercept are converted back to the standard co-ordinate frame using the below relations

For a regression X on Y (standard OLS)

$$y = mx + c \qquad (1)$$

which, given a neutral comfort score of k means

$$T_c = \frac{k - c}{m}$$

equivalently, for a regression of Y on X, in the co-ordinate system of X on Y.

$$y = m'x + c'$$

$$T_c{}' = \frac{k - c'}{m'}$$

To calculate $T_c{}' - T_c$ the relations $m' = \frac{m}{R^2}$ and $c' = \overline{y} - m'\overline{x}$ are used (where R^2 is the square of the correlation coefficient and the bar denotes the mean), yielding

$$T_c{}' - T_c = \frac{1}{m}(1 - R^2)(\overline{y} - k)$$

Using this relation for the SCATs data for free running UK offices, with a value of k = 4, $T_c{}' - T_c$ = 1.1°C

7. Appendix 2

The log likelihood function which is maximised is given by

$$\ln\Big(p\big(y\big|x, m, b, \sigma_x, \sigma_y\big)\Big) = \frac{1}{2}\sum_n \frac{(y_i - mx_i - b)^2}{\sigma_y^2 + (m\sigma_x)^2}$$

8. References

Adcock, R.J. 1878. A problem in least squares. *The Analyst*. 5 (2): 53–54.

Cheng, C.L., Van Ness, J.W. 1999. *Statistical Regression with Measurement Error: Kendall's Library of Statistics 6*. London: New York: Wiley

D'Agostini, G. 2005. Fits, and especially linear fits, with errors on both axes, extra variance of the data points and other complications. arXiv:physics/0511182.

de Carli, M., Olesen, B.W., Zarrella, A., Zecchin, R., 2007. People's clothing behaviour according to external weather and indoor environment. Building and Environment, *Indoor Air 2005 Conference* 42, 3965–3973.

de Carvalho, P.M., da Silva, M.G., Ramos, J.E., 2013. Influence of weather and indoor climate on clothing of occupants in naturally ventilated school buildings. *Building and Environment* 59, 38–46.

Deming, W.E. 1943. *Statistical adjustment of data*. New York: Wiley.

Dehghan, H., Mortzavi, S.B., Jafari, M.J., Maracy, M.R., 2015. Development and Validation of a Questionnaire for Preliminary Assessment of Heat Stress at Workplace. *J Res Health Sci* 15, 175–181.

Foreman-Mackey, D., Hogg, D.W., Lang, D., Goodman, J., 2013. emcee: The MCMC Hammer. *Publications of the Astronomical Society of the Pacific* 125, 306–312.

Fuller, W. 1987. *Measurement Error Models*. New York: Wiley

Kummell, C.H. 1879. Reduction of Observation Equations Which Contain More Than One Observed Quantity. *The Analyst*, 6(4), 97–105

Glaister, P. 2001. Least squares revisited. *The Mathematical Gazette*, 85(502), 104-107.
Hausman, J. 2001. Mismeasured Variables in Econometric Analysis: Problems from the Right and Problems from the Left. *Journal of Economic Perspectives*. 15(4), 57-67.
Hogg, D.W., Bovy, J,. Lang. D. 2010. Data analysis recipes: Fitting a model to data. arXiv:1008.4686
Humphreys, M.A. 1977. The optimum diameter for a globe thermometer for indoor use *Annals of Occupational Hygiene,* 20 (2), 135-140
Humphreys, M.A., Nicol, F., Roaf, S., 2016. Adaptive Thermal Comfort: Foundations and Analysis. London: New York: Routledge
Khogare, D.T., Sarambekar, H.L., Manvar, V.S., 2011. Satisfaction Scale for Measuring Thermal Comfort and Illumination in Office. *Journal of Human Ecology* 35, 71–74.
Lundgren, P., Henriksson, O., Kuklane, K., Holmér, I., Naredi, P., Björnstig, U., 2014. Validity and reliability of the Cold Discomfort Scale: a subjective judgement scale for the assessment of patient thermal state in a cold environment. *J Clin Monit Comput* 28, 287–291.
Meteorological Office 2009 UKCP09: Gridded Observation Data Sets. Retrieved from: https://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/faq.html
Morgan, C., de Dear, R., 2003. Weather, clothing and thermal adaptation to indoor climate. *Climate Research* 24, 267–284.
Nicol, J.F., McCartney, K. 2000. *Smart Controls and Thermal Comfort Final Report* Oxford, Oxford Brookes University
Nicol, J. F., Humphreys, M. A, 2010. Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. Building and Environment, *International Symposium on the Interaction between Human and Building Environment Special Issue Section* 45, 11–17.
Nicol, F., Humphreys, M., Roaf, S., 2012. *Adaptive Thermal Comfort: Principles and Practice.* London: New York: Routledge
Rao, C., R., 1973. *Linear statistical inference and its applications*. New York: John Wiley & Sons.
Schweiker, M., Fuchs, X., Becker, S., Shukuya, M., Dovjak, M., Hawighorst, M., Kolarik, J., 2017. Challenging the assumptions for thermal sensation scales. *Building Research & Information* 45, 572–589.
Shipworth, D., Huebner, G., Schweiker, M., Kingma, B., 2016. Diversity in Thermal Sensation: drivers of variance and methodological artefacts. In: Brotas, L. and Roaf, S. and Nicol, F. and Humphreys, M.A., (eds.) *Proceedings of the 9th International Windsor Conference 2016:* making comfort relevant. (pp. 56-72). Network for Comfort and Energy Use in Buildings (NCEUB)
Sivia, D.S., Skilling, J., 2006. *Data analysis: a Bayesian tutorial*. Oxford University Press. Oxford.
Smith, C.L., Webb, A., Levermore, G.J., Lindley, S.J., Beswick, K., 2011. Fine-scale spatial temperature patterns across a UK conurbation. *Climatic Change* 109, 269–286.
Smith, G.D., Phillips, A.N., 1996. Inflation in epidemiology: “the proof and measurement of association between two things” revisited. *BMJ* 312, 1659–1661.
Spearman, C (1904). "The proof and measurement of association between two things". *American Journal of Psychology*. 15: 72–101
Trochim, W., M., Donnelly, J., Arora, K., 2016. *Research Methods: The Essential Knowledge Base, 2nd Edition*. Wadsworth Publishing. Belmont.
Vallverdú, J., 2016*. Bayesians versus Frequentists: A Philosophical Debate on Statistical Reasoning* London: Springer.
Wilson, M., Solomon, J., Wilkins, P., Jacobs, A., Nicol, F., 2000. *Smart Controls and Thermal Comfort Project: Final Report Task 1*. Low Energy Architecture Research Unit (LEARN) University of North London

9. Acknowledgements

The authors are very grateful to Michael Humphreys for extensive discussions during the development of this paper, as well as Jane Galbraith and Rex Galbraith for comments at the review stage.

SESSION 7

Sleep, IEQ and Energy

Invited Chairs:
Susan Roaf and Kevin Lomas

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Room temperature during sleep

Fergus Nicol [1] and Michael Humphreys [2]

[1] Cass School of Art, Architecture and Design, London Metropolitan University, Calcutta House, London E1 7NT; f.nicol@londonmet.ac.uk
[2] School of Architecture, Oxford Brookes University, Oxford OX3 OBP

Abstract. There is pressure in the UK to limit the temperatures in bedrooms to below 26°C to avoid overheating. This short paper looks at the temperatures in bedrooms and uses data from comfort surveys combined with models which link comfort to the thermal environment. Evidence is given that people sleep comfortably at temperatures of 29 - 31°C in their personal space within the bed and they use bedclothes to allow them to attain these temperatures. The effect of the use of a mattress and the adaptive opportunities afforded by the bedclothes and sleepwear are briefly explored as are methods used in hot climates to offset high bedroom temperatures.

Keywords sleep, comfort, bedclothes and sleepwear, energy

1. Introduction

1.1. Acceptable bedroom temperature

The environmental temperature in the bedroom is known to have an effect on the quality of the sleep which the occupant can expect. One investigation of this is presented in the first chapter of CIBSE Guide A (2015) Chapter 1, page 1-16. The researcher (Humphreys 1979) has plotted the temperature against the number of blankets the subject used (Figure 1). The subjects were living in England and all except one wore pyjamas or a nightdress[1]. Also shown is the quality of sleep the subject experienced (on a five-point scale from good to bad).

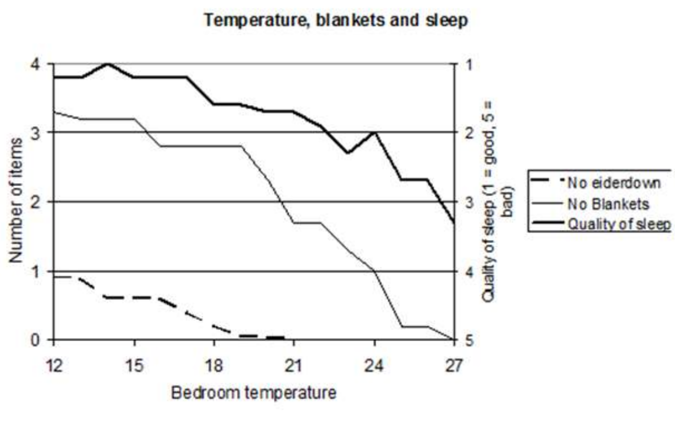


Figure 1. The effect of bedroom temperature upon bedding and quality of sleep (Humphreys 1979)

In the CIBSE (2017) Technical Memorandum TM59, this study has been cited amongst others to justify a recommendation to limit temperatures in dwelling bedrooms to less than 26°C, because it gives some evidence that, in the UK, bedroom temperatures over 26°C may be experienced as "bad" for sleep quality, (particularly for those in double beds). But in view

[1] Humphreys recalls, from talking with respondents about their sleeping patterns.

of the likelihood that building designers will resort to financially and environmentally expensive mechanical cooling if they expect the room to be overheated, there is a need to revisit existing literature to ensure that this will not unnecessarily lead to increased energy use and impacts on occupant's quality of life and the environment. Recent advice from the Department of communities and Local Government (DCLG) will push designers into following the advice of TM59, so potentially increasing uptake of air-conditioning in UK homes.

Part of the reason for this reconsideration is the changes which have taken place in bedding since much of the historic experimental work was undertaken. Firstly the accepted bed clothing nowadays is the duvet, providing different seasonal grades of insulation and, or, sheets. Bedclothes now seldom include blankets or eiderdowns[2]. As well as changing the range of insulation available to the sleeper to adapt to bedroom temperature, this change in bedding may have also led to a change in their sleepwear.

Bedrooms are often found in the upper part of the house, and their windows may be kept closed during the day when they are unoccupied, so they could be particularly likely to be hot in summer. But adaptive opportunities such as external shading or shuttering, or improved window opening and security opportunities do not appear in the palette of proposals supplied by CIBSE in their advice to designers. The only solution in their cooling repertoire is a straight move to a mechanical solution, with obvious cost consequences for building owners and users. Getting the correct upper limit for the bedroom temperature is therefore particularly important, as it may also encourage more passive solutions to problems of sleep heat-disturbance.

1.2. Weaknesses in the TM59 model

R K Macpherson (1973) considered the basic requirement of the sleeping person. He quotes an experiment in which the mean temperature close to the body of sleeping subjects was measured and found to be about 28^{o}C. This is similar to that reported by McIntyre (1937) (27-29^{o}C) and Haskell (1981) (29^{o}C). Kingma (Kingma et al 2012 and 2017) and his colleagues of Maastricht University report that the 'thermoneutral zone' of the human body (the band of temperature within which neither sweating nor shivering is necessary) lies between 28 and 32^{o}C. A temperature of 28-30^{o}C under the bedclothes and close to the body suggests the comfortable operative temperature in the room would be one which allows the sleeping person to achieve a temperature of about 29^{o}C close to the body. This estimate is in the absence of air movement, as it was taken under the bedclothes close to the subject.

Djongyang (2012) and his co-workers, using a mixture of theory and climate chamber studies, have suggested thermo-neutral operative temperatures in the region of 29-32^{o}C for nude subjects in desert climates. They quote a number of papers which have come to the same or a similar sleep temperature for nude subjects. The argument could be advanced that the temperature which people require for comfortable sleep is in the region of 30^{o}C. The function of the bedclothes and sleepwear is to provide a microclimate at that temperature in the vicinity of the skin surface when they are asleep.

Lan et al (2014) measured sleep quality for subjects in a climate chamber and wearing light sleepwear and a blanket, at three temperatures: 23^{o}C, 26^{o}C and 30^{o}C and found that proportion of subjects reporting 'sufficient sleep' at 26^{o}C, was greater that at either 23^{o}C or 30^{o}C. In addition 26^{o}C was less likely to cause thermal discomfort either before or during the sleep period.

[2] feather-filled items which were similar to the duvet but smaller and often used as an addition to the blankets in cold weather

Obradocich et al (2017) showed that human sleep loss is also affected by the weather, in that greater sleep loss is indicated when the outdoor temperature is hotter than normal for the time of year.

2. Modelling comfort in bedrooms

2.1. Heat balance for sleeping people

There is some complexity in the thermal pathways to the room environment from the body beneath the bedclothes and the sleepwear. Heat is lost in many directions and through different combinations of coverings: downwards through the sleepwear, sheet and mattress; upwards through the sleepwear sheet and blankets or duvet, and sideways into the air around the body, and maybe movements of the body allow air to escape or enter the 'capsule' of air surrounding the sleeper. In addition there is the heat loss directly from the uncovered parts of the body such as the face and limbs exposed during sleep. In addition heat is also lost through respiration and sweating. A useful model of the heat loss pathways is given by Pan et al (2010).

There is an additional complication when the subject is in a bed with the highly insulated sprung mattress as used in many countries. In summer, when the clothing above is light, the body is losing heat almost entirely through that part which is not in contact with the mattress. This is physically equivalent to increasing the metabolic rate by about 20% because the proportion which is in contact with the mattress is about 20% of the area of the whole body (Pan et al 2010, Raja and Nicol 1997).

In hot climates there are a numbers of ways in which people avoid the problem of being too hot in bed without the use of mechanical cooling. Some are listed below:

- using a bed without the insulated mattress (for example using a string mattress)
- using a fan to provide air movement
- wrapping themselves in a 'sleeping cloth' which in hot conditions will become wet and thereby reduce its insulation, spread the sweat, increase evaporation, and prevent disturbance from sweat running down the skin
- move to another place (for instance on to the roof to take advantage of radiant cooling to the sky) or into a cool basement

2.2. Room temperature for comfort in physiological models

Humphreys' simple 1970 model of the thermal relationship between clothing, metabolic rate and operative temperature is illustrated in Figure 2. This (approximate) model suggests that the temperature comfort zone is 29-31^{o}C and with the increase in the effective metabolic rate to 60wm^{-2} to allow for a mattress it is 27.5-30^{o}C. The maximum comfort temperature for the sleeping unclothed body (above which an increase is required in sweat rate to maintain the thermal equilibrium) is therefore about 31.5^{o}C - or 30.0^{o}C with allowance for a mattress. A development of the Humphreys diagram (Humphreys et al (2016) chapter 20) suggests these maximum temperatures can be increased to 33.5^{o}C (32.5^{o}C with mattress) if the air speed is increased to 1m/s.

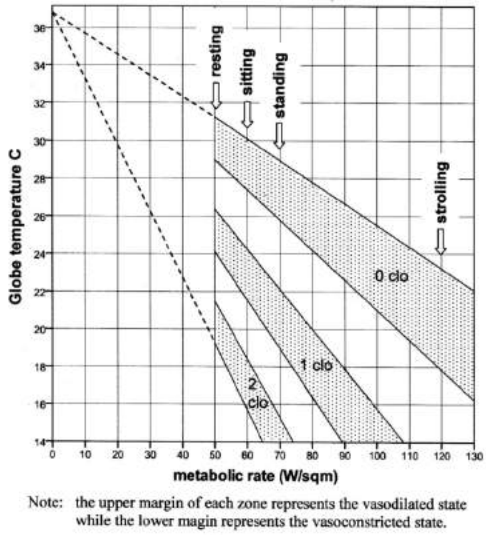


Figure 2, Humphreys 1979 schematic diagram of comfort zoned for still air and various levels of clothing (from Humphreys et al 2016 chapter 20)

The optimum (PMV = 0) sleeping temperature is predicted by Fanger's (1972) PMV index for nude people at minimal metabolic rate and no bedclothes or sleepwear covering is 30.4°C. Fanger gives 32°C for air speed of 1.5 m/s. To allow for a mattress we can increase the metabolic rate by 20% from 0.8 met to 1.0 met; then the temperature at which there is a balance between heat production and heat loss is reduced to 28.8°C. The upper temperature limit to avoid heat discomfort (PMV=0.5) is 31.1°C or 29.7°C with mattress. These temperatures can again be increased by about 2-3K by an increase in air speed to 1m/s[3].

This analysis suggests that the maximum comfort temperature for nude sleeping people is about 3-5K above the 26°C suggested by TM59. The low values of temperature suggested by Humphreys in 1979 may be explained by the sleeping habits of the UK subjects. It is not recorded what night clothes the subjects were wearing but some sort of light sleepwear was the norm at the time of the surveys, added to which a light cotton sheet would have been normal, bringing the equivalent clothing insulation up to approximately 0.4 -0.6Clo. Using Fanger's PMV this set-up would give a resting comfort temperature of about 26.5°C, and the temperature-limit for (PMV= +0.5) would have been 27.9°C. Using the Humphreys diagram would suggest a comfort temperature of 26.0°C and an upper limit of 27.5°C

2.3. Bedclothes

Bedclothes such as sheets and blankets and duvets have an important function in making the bed occupants comfortable and safe. The metabolic rate of a sleeping person is low and as the body prepares for sleep vasodilation occurs which facilitates heat loss and this signals a drop in body temperature and a simultaneous increase in the temperature of distal parts such as hands and feet (Krauchi, 2007). As a consequence of these changes the temperature regime in the bed becomes an important part of the quality of sleep and the maintenance of body temperature is a part of this.

The thermal insulation of bedclothes is measured in Togs which roughly translate to the more familiar clo units according to the ratio 1 clo ≈ 1.55 tog. Commonly a summer duvet is about 3 Tog (about 2 clo) and a winter duvet about 9 Tog (about 6 clo). The Humphreys model

[3] All estimates in these PMV calculations use the Berkeley 'CBE Thermal Comfort Tool' which is available on the internet at http://comfort.cbe.berkeley.edu/t

suggests that, in the resting metabolic rate, each clo of insulation reduces the comfort temperature by about 5K ignoring the mattress or 6K including the mattress. This suggests that the summer duvet is appropriate at bedroom temperatures of around 21.5°C without a mattress or 18°C with a mattress. The winter duvet should provide comfort down to just above 0°C, or even lower in combination with a highly insulating mattress and/or under-blanket.

The way in which a duvet is used can be very adaptive. They are not normally 'tucked in' under the mattress as were blankets and this allows the users to move themselves around and adjust the bedclothes to their personal needs (Figure 3) During cold conditions this could be a problem if cold air from the room infiltrates or the exposed parts of the body get too cold, so the above calculated values of the comfort temperature with a winter duvet may be too low. However, in a cold room many will tend to sleep curled up, with the limbs and even the head under the cover of the duvet. Air movement is another adaptive opportunity as suggested by Lan et al (2013) in a study of personal ventilation.

The success of the adaptive use of bedclothes is indirectly illustrated by the finding by Imagawa et al (2015a) following a survey in 25 houses in Japan. From an analysis of over 3000 assessments of the effect of temperature on sleep in bedrooms with indoor air temperatures between 21 -34°C Imagawa and Rijal (2015b) that "there was no distinctive relationship between the depth of sleep reported by the subjective vote and indoor air temperature".

Figure 3 illustrating the ability of a young duvet user to adjust the bedclothes to suit his needs (from Nicol et al 2012, photograph by R. H. Roberts)

3. Discussion

This short paper suggests that a model of the dependence of comfort and sleep quality on bedroom temperature could start with the observation suggested by a number of researchers that the temperature of the immediate microclimate around the sleeper should be around 29-32°C. This finding is strengthened by the use of two thermal models of the human body (Humphreys and PMV) which suggest a similar comfort temperature for nude sleeping subjects in the absence of air movement. The role of sleepwear and bedclothes is then to allow the sleeping person to adapt to the temperature in the bedroom. This is primarily a behavioural adaption of the person to the conditions in the bedroom. Other adaptive responses would be to modify the temperature in the room using heating or cooling devices or passive means as are suggested (for hot conditions) in the bullet points in section 2.1 above. The desirability of further research of the microclimate in the bed and its relationship to bedroom temperature is indicated.

4. Conclusions

- The temperature of the immediate space around a sleeping person should be about 30^{o}C to ensure comfort and adequate sleep.
- The purpose of the bedding is to allow the sleeping person to achieve this temperature in their immediate personal space within the bed.
- The maximum temperature in bedrooms to avoid discomfort and sleep loss is therefore a function of the bedroom environment (temperature and air movement) and the available adaptive opportunities including sleepwear and bedding.
- The use of a well-insulated mattress lowers the room temperature the occupant will find comfortable.
- Bedroom occupants use bedding as an adaptive opportunity at temperatures which would otherwise make sleep difficult

5. References

CBE Thermal Comfort Tool (http://comfort.cbe.berkeley.edu/).

CIBSE, 2015. CIBSE Guide A, Environmental Design Chapter 1: Environmental Criteria for Design, London, Chartered Institution of Building Services Engineers

CIBSE, 2017. TM59 Design methodology for the assessment of overheating risk in homes. London, Chartered Institution of Building Services Engineers

Djongyang, N, Tchinda, R and Njomo, D, 2012. Estimation of some comfort parameters for sleeping environments in dry-tropical sub-Saharan Africa region, Energy conversion and management, 58 110-119

Fanger, PO, 1970. Thermal Comfort New York, McGraw Hill

Haskell, EH, Palca, JW, Walker, JM, Berger, HJ and Heler HC, 1981. Metabolism and thermoregulation during stages of sleep in humans exposed to heat and cold Journal of Applied physiology Respiratory Environmental and Exercise Physiology, 51 948

Humphreys, M A, 1979. The influence of season and ambient temperature on human clothing behaviour Proc International Climate Symposium, Copenhagen, September 1978

Humphreys, MA, 1970. A simple theoretical derivation of thermal comfort conditions. Journal of the Institution of heating and ventilating Engineers, 38, 95-98

Humphreys, MA, Nicol, JF, and Roaf, SC, 2016. Adaptive Thermal Comfort, Foundations and Analysis, London, Routledge. (Chapter 20 pp 182-19)

Imagawa, H., Rijal, HB., and Shukuya, M., 2015a. Field survey on the comfort temperature and occupant behaviour in bedrooms (in Japanese)

Imagawa H., Rijal HB., 2015b. Field Survey of the thermal comfort, quality of sleep and typical occupant behaviour in the bedrooms of Japanese houses during the hot and humid season. Architectural Science Review, 58(1) 11-23

Kingma, B. R., Frijns, A., and van Marken Lichtenbelt, W. D., 2012. The thermoneutral zone: implications for metabolic studies. *Frontiers in Bioscience, Elite edition*, *E4*, 1975-1985. DOI: 10.2741/e51

Kingma, B., Schweiker,M., Wagner, A. and van Marken Lichtenbelt, W. 2017 Exploring a biophysiological model to understand thermal sensation, Building Research and Information vol. 45(7)

Krauchi, K, 2007. The thermophysiological cascade leading to sleep initiation in relation to phase of entrainment. Sleep Med. Rev. 11 439-451

Lan, L., Pan, L., Lian, Z., Huang, H. and Lin, Y., 2014. Experimental study of thermal comfort of sleeping people at different air temperatures, Building and Environment, 73, 24-31

Lan, L., Lian, Z., Zhou, X., Sun, C., Huang, H., Lin, Y. and Zhou, Y. 2013. Pilot study on the application of bedside personalized ventilation to sleeping people, Building and Environment 67 150-166

Macpherson, RK, 1973. Thermal stress and thermal comfort, Ergonomics 16(5) 611-622

McIntyre, J, 1937. Discussion of the effect of water vapour content… JIHVE 4, 570-601

Nicol, JF, Humphreys, MA and Roaf, SC, 2012. Adaptive thermal comfort: Principles and Practice, London, Routledge

Obradovich, N., Migliorini, R, Mednick, S. and Fowler, J, 2017. Nightime temperature and human sleep loss in a changing climate Science Advances 3 e.1601555

Pan, D, Lin Z and Deng, S, 2010. A mathematical model for predicting the total insulation value of a bedding system, Building and Environment 45 1866-1872

Raja, I.A. and Nicol, J.F., 1997. A technique for postural recording and analysis for thermal comfort research Applied Ergonomics 28 (3) pp. 221-225

A research on the effects of indoor environment on sleep quality

Nan Zhang[1, 2], Bin Cao[1, 2] and Yingxin Zhu[1, 2]

[1] Department of Building Science, School of Architecture, Tsinghua University;
[2] Key Laboratory of Eco Planning & Green Building, Ministry of Education (Tsinghua University)

Abstract: Sleep is an important behaviour for humans to maintain good physical and psychological status after a day's work. Indoor environment, along with many other factors such as emotion and body condition, can disturb our daily sleep. To explore the effects of indoor environment on sleep quality quantitatively, a field study was conducted in university dormitories. The field study included the measurement of environmental parameters (ambient temperature, relative humidity, black globe temperature, airflow velocity, noise level, illumination intensity, concentration of CO_2 and $PM_{2.5}$), measurement of physiological parameters (heart rate and wrist skin temperature), and subjective questionnaire (before and after sleep). Environmental and physiological parameters during nocturnal sleep are different with those during non-sleep time. The satisfaction range of different environmental parameters for occupants' to fall asleep were analysed. Subjects feel more neutral and less sensitive to thermal environment during sleep. Multiple-factor analyses were applied to figure out the impacts of different environmental factors on sleeping environment satisfaction. This study indicates that several environmental factors, which may disturb sleep, are interrelated and need more transactional analysis and research.

Keywords: Sleep environment; sleep quality; field study

1. Introduction

Humans spend almost a third of the lifetime on sleeping. Sleep is such an important behaviour that can help us wipe out tired feelings, recover energy, protect the brain from damage and promote young people's growth(Siegel, 2005). Moreover, lack of sleep or poor sleep may cause body system damage, such as mild cognitive impairment, increasing type 2 diabetes and cardiovascular disease risk, impairing immune system. Sleep problems can even lead to growth inhibition and obesity.

Sleeping issues have drawn worldwide attention during recent years. According to a worldwide investigation, sleep problems threaten health and quality of life for up to 45% of the world's population and 35% of people do not feel they get enough sleep, affecting both their physical and mental health.

Indoor environment as well as bed micro-climate, psychological states, body conditions and circadian rhythms can impact daily sleep. Improvement of indoor environment and bed micro-climate can have positive effects on sleep quality(Lan et al., 2017). Many researches have emphasised on this aspect.

Indoor environment can be separated into thermal environment, acoustic environment, lighting environment and indoor air quality (IAQ). The four kinds of environments have different influences on sleep quality(Pigeon and Grandner, 2013). Many studies reported that lighting affects sleep in terms of biological rhythms instead of comfort satisfaction(Kripke et al., 2007). Too much light at night makes sleep difficult to initiate or maintain. Sudden and loud noises can also disrupt sleep. The effect of noise depends on a number of factors, including sleep stage, salience of the noise, habituation to the noise, the presence of other noise in the environment and individual differences(Pirrera et al., 2010). Significant correlations were found between night noise disturbances and sleep outcomes (Pirrera et al., 2014, Griefahn et al., 2000, Brink, 2011). However, no clear indication of a direct impact of objectively measured noise on sleep was found in this study. The thermal requirement of sleeping people has become the research focus during last few years. It has been recognized that 29°C is neutral temperature for naked human in sleep(Haskell et al., 1981). However, a general determination method for neutral temperature remains to be established, which can be applied to different bedding insulation and sleeping habits. Very few studies have explored relationships between sleep and indoor air quality (IAQ).

Although thermal environment, acoustic environment, lighting environment and IAQ are essential for occupants to have a good sleep, their influence mechanisms are still unclear. This study aims to figure out the relationship between environmental factors and sleep quality based on subjective questionnaire and objective measurement.

2. Methods

A field study including measurements of indoor environmental parameters and investigations of respondents' subjective sensations was conducted in student dormitories in Beijing in 2017. This field study lasted for six weeks excluding weekends and holidays. Twenty-four subjects participated in the field study and the male/female ratio is 1:2. All subjects are university students with an average age of 19.7. Their average body mass index (BMI) is 22.0, which is within the normal range. In addition, all the subjects have no sleep disorder. Four students live in the same dormitory equipped with four loft beds with desks.

Environmental parameters, such as ambient temperature, relative humidity, black globe temperature, airflow velocity, noise level, illumination intensity, concentration of CO_2 and $PM_{2.5}$, were measured. Except for airflow velocity, all the environmental parameters were recorded continuously. Airflow velocity was measured with and without windows open. Under the two conditions airflow velocities were both lower than 0.2m/s.

In addition, subjects were asked to complete questionnaires before and after nocturnal sleep every day. The pre-sleep questionnaires investigate subjects' evaluations of temperature, noise, lighting and IAQ, as well as their active states, beddings and clothing conditions. Post-sleep questionnaires mainly reflect subjects' evaluations of environments during sleep through recollections. Besides, their self-evaluations of sleep quality are also included in post-sleep questionnaire. Table 1 shows the six scales to evaluate sleep quality used in post-sleep questionnaire. According to previous researches, subjects' perceptions of the six questions were shown to consistent with the results of EEG (electroencephalogram) measurements. Totally 259 questionnaires were acquired and 220 of them were valid.

Table 1. Scales for sleep quality assessment

Scale	Ease of falling asleep	Calmness of sleep	Night-time awakening frequency	Satisfaction about sleep	Ease of awakening	Freshness after awakening
1	Very difficult	Very restless	Never	Very dissatisfied	Very difficult	Very fatigue
2	Quite difficult	Quite restless	1 to 2 times	Quite dissatisfied	Quite difficult	Quite fatigue
3	Neither difficult nor easy	Neither restless nor calm	3 to 4 times	Moderate	Neither difficult nor easy	Neither fatigue nor refreshed
4	Quite easy	Quite calm	often	Quite satisfied	Quite easy	Quite refreshed
5	Very easy	Very calm	—	Very satisfied	Very easy	Very refreshed

3. Results and discussions

3.1. Environmental parameters

Several environmental parameters have been continuously recorded in the field study. Figure 1 shows the indoor air temperature and humidity ratio of nocturnal sleep time and non-sleep time during a typical week. The sleep period and non-sleep period are defined by the recorded average sleep latency and waking time in the morning for all the subjects, which are 1:31 and 8:13 respectively. It can be concluded that indoor air temperature of sleep time is lower than that of non-sleep time regularly. On the contrary, humidity ratio of sleep time is higher than that of non-sleep time. The hourly ratios of indoor and outdoor concentration of $PM_{2.5}$ are shown in Figure 2. At the beginning of sleep, the I/O of $PM_{2.5}$ are very small and fluctuate within a narrow range. Figure 3 and Figure 4 show the average minutely value of CO_2 concentration and noise level during the entire measuring period. The concentration of CO_2 tends to get higher in the night and stands steady at the average value of 1750ppm at about three o'clock. The average noise level during nocturnal sleep is 41.5dBA.

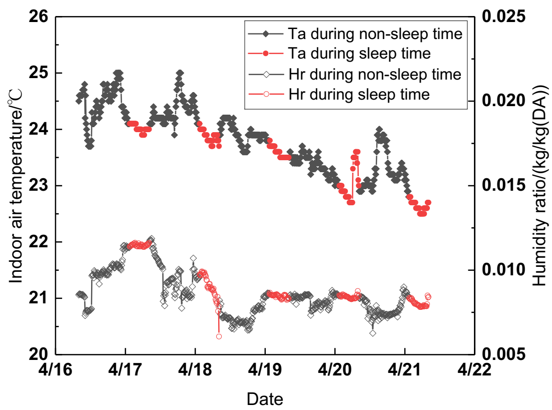


Figure 1. Indoor air temperature and humidity ratio during a typical week

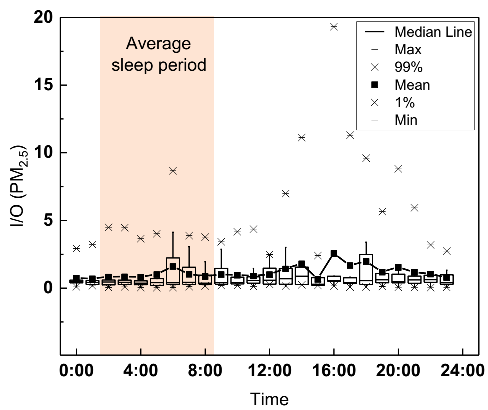


Figure 2. Hourly ratios of indoor and outdoor concentration of $PM_{2.5}$

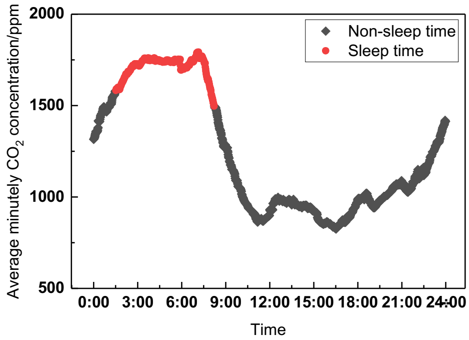


Figure 3. Average minutely value of CO_2 concentration

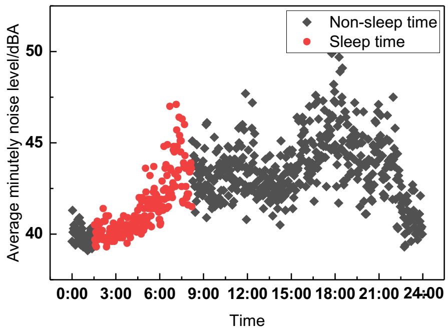
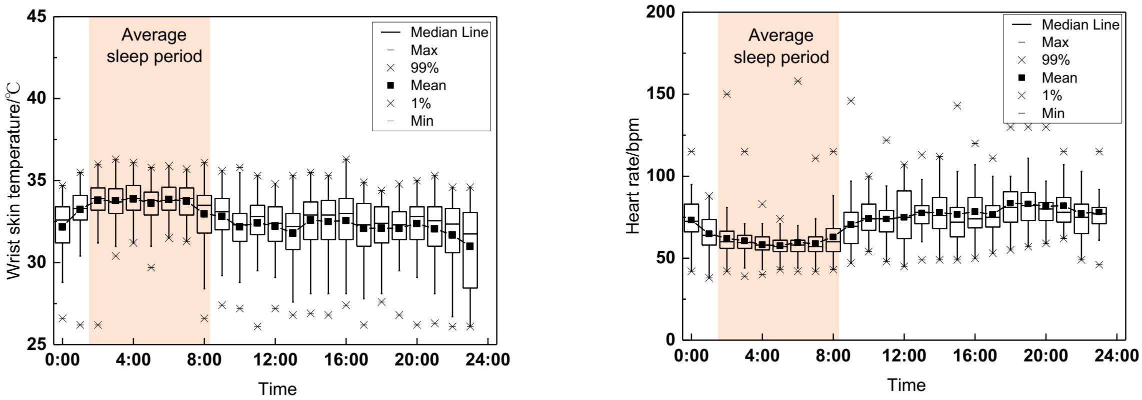


Figure 4. Average minutely value of noise level

3.2. Physiological parameters

Physiological parameters are essential for distinguishing between sleeping and awakening. In this field study, two physiological parameters (wrist skin temperature and heart rate) were hourly recorded. There are significant differences between sleeping and awaking, as shown in Figure 5. The average skin temperature of wrist during sleep is 33.8°C, which is 1.6°C higher than that during awakening. The average heart rate during sleep is 60ppm while the average heart rate of awake subjects is 75ppm. This result is in accord with K. Kräuchi (2000)'s research.



(a) (b)

Figure 5. Physiological parameters. (a) Wrist skin temperature. (b) Heart rate.

3.3. Sleep environment satisfaction and sleep quality satisfaction

Subjects responded their sleep environment satisfaction and sleep quality satisfaction as soon as they got up. Figure 6 shows subjects' satisfaction about thermal environment, acoustic environment, lighting environment, IAQ and the overall sleeping environment.

Except for lighting environment, subjects' evaluations of satisfaction have similar distribution. In this field study, subjects were more satisfied with lighting environment than other environment and the overall sleep environment.

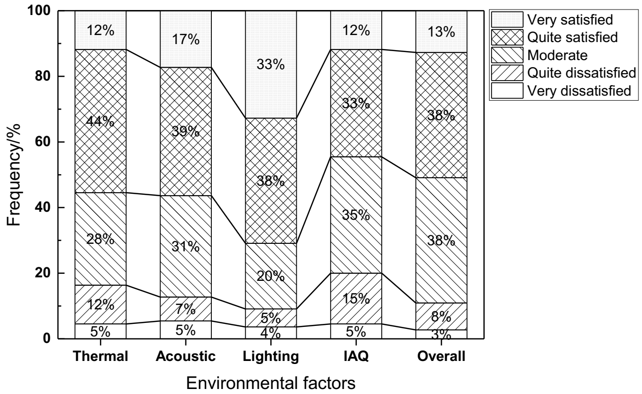


Figure 6. Subjects' satisfaction about thermal environment, acoustic environment, lighting environment, IAQ and the overall sleep environment

Figure 7 illustrates the relationship between subjects' sleeping environment satisfaction (SES) and sleeping quality satisfaction (SQS). An excellent linear relationship can be described as follow:

$$SQS=0.949\times SES+0.01,\ R^2=0.982$$

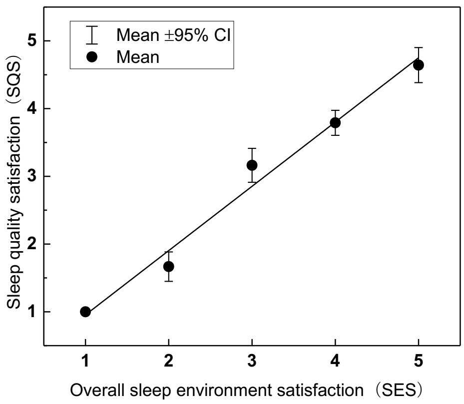


Figure 7. Subjects' sleeping environment satisfaction (SES) and sleeping quality satisfaction (SQS)

Subjects' thermal environment satisfaction (STS) and IAQ satisfaction (SAS) during sleep changing against average operative temperature and CO_2 concentration during sleep, respectively. Relationships environment satisfaction and environmental parameters can be described as follows:

$$STS=-0.08\times T_{op}^2+4.02\times T_{op}-44.69,\quad R^2=0.446$$

$$SAS=9.66\times \exp\left(-C/264.82\right)+2.78,\quad R^2=0.720$$

It is concluded that the most satisfied operation temperature is 24.2°C and subjects' IAQ satisfaction (SAS) during sleep remains unchanged when CO_2 concentration is higher than 1880ppm. Besides, subjects' acoustic environment satisfaction (SNS) were also analysed. However, no significant difference or relationship has been found between SNS and average noise level during sleep.

3.4. Thermal sensation

Some research have proved that subjects' thermal sensations during sleep and awake period are different(Song et al., 2016). This study also compares subjects' thermal sensation before sleep (wake) and during sleep (recall after night-time sleep). Figure 8 illustrates the thermal sensation changing against operation temperature during sleep (TSV_s) and awake (TSV_w). People during sleep have lower neutral temperature and wider accepted temperature range. Lower metabolic rate and higher insulation during sleep may lead to the results.

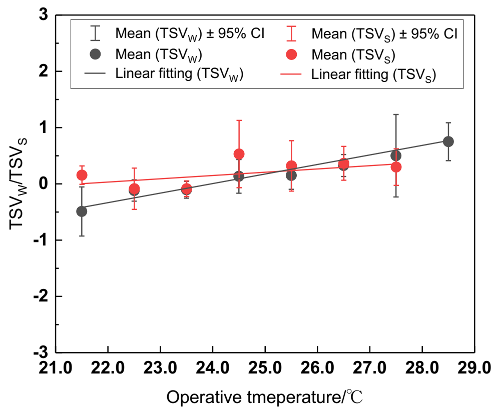


Figure 8. Thermal sensation during sleep (TSVs) and awake (TSVw)

3.5. Multiple-factor analysis

Multivariate regression analysis is used to predict the value of one or more responses from a set of predictors. It can also be used to estimate the linear association between the predictors and responses. In this case, multivariate regression analysis can be applied to analyse the relationship between different environmental factors and sleep quality. The linear regression model has the form:

$$Y = a_0 + a_1 \times x_1 + a_2 \times x_2 + \cdots + a_n \times x_n$$

where $x_1,x_2,\ldots,x_n$ are a set of predictors believed to be related to a response variable Y and $a_0,a_1,\ldots,a_n$ are unknown (and fixed) regression coefficients. Least squares estimation method is used to determine the regression coefficients(Schervish, 1987). The following is regression result:

$$SQS=0.240+0.177\times STS+0.294\times SNS+0.195\times SLS+0.224\times SAS,\ R^2=0.410$$

SAS, STS, SNS, SLS and SAS are sleep quality satisfaction, sleeping thermal environment satisfaction, sleeping acoustic environment satisfaction, sleeping lighting environment satisfaction and sleeping IAQ satisfaction respectively. The regression coefficients of different environment satisfactions reveal their impacts on sleep quality satisfaction. The regression coefficient of sleeping acoustic environment satisfaction is the highest while the regression coefficient of sleeping thermal environment satisfaction is the lowest. However, the indoor air temperature during the field study period is around the neutral scope and almost inside the acceptable range, which probably explains the reason why occupants are less sensitive to the thermal environment during sleep. More field studies are needed in this research to reveal the interaction relationship between different environmental factors and sleep quality.

Multivariate regression analysis can easily obtain the weight coefficients of different environmental factors, based on the hypotheses of linear correlation between independent variables and dependent variable and exclusiveness of independent variables. However, Huang et al. (2012) proved that the satisfaction levels of both temperature and noise have one-vote veto power over the satisfaction level of the office indoor environment. Figure 9 illustrates the ratio of environment-related dissatisfaction among subjects with unsatisfactory sleep quality. Sixty-five percent of these subjects were unsatisfied with sleeping environments (gave the evaluation of scale 1 or 2), which again emphasizes the importance of the sleeping environments. Among unsatisfied environmental factors, single, double and multiple factors are account for 46%, 39% and 15% respectively. Besides, thermal environment takes a larger proportion of the unsatisfied environmental factors than acoustic environment, lighting environment and IAQ, as shown in Figure 10. The analysis result of subjects who had poor sleep quality is inconsistent with the result of multivariate regression, indicating that thermal environment is still a considerable influencing factor during sleep. Further researches may focus on the laboratory experiments which can precise control of different environmental factors.

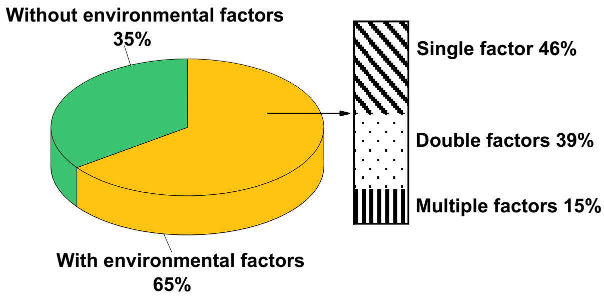


Figure 9. The ratio of environment-related dissatisfaction among subjects with unsatisfactory sleep quality.

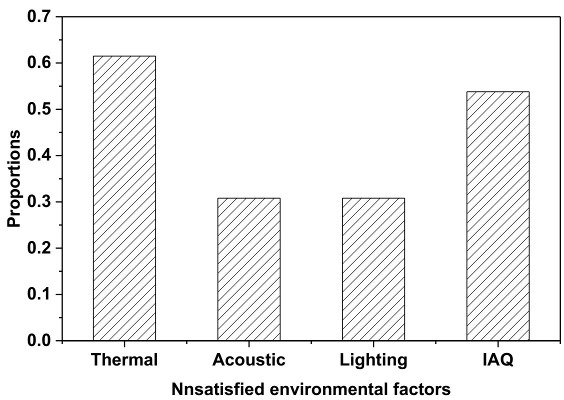


Figure 10. Proportions of unsatisfied environmental factors

4. Conclusions

This study aims to figure out the relationship between indoor environment and sleep quality based on subjective questionnaire and objective measurement. Conclusions achieved in this study are:

There are distinctions in indoor air temperature and relative humidity between sleeping period and non-sleeping period. The concentration of CO_2 tends to get higher in the night and stands steady at the average value of 1750ppm. The average noise level during nocturnal sleep is 41.5dBA. The physiological parameters (wrist skin temperature and heart rate) during sleeping are quite different from that during awakening.

In field study, subjects were more satisfied with lighting environment than other environment and the overall sleep environment. Subjects' sleeping environment satisfaction (SES) and sleeping quality satisfaction (SQS) show an excellent linear relationship. The most satisfied operation temperature is 24.2°C and subjects' IAQ satisfaction (SAS) during sleep remains unchanged when CO_2 concentration is higher than 1880ppm.

Different thermal sensations during sleep and awake period were observed. Moreover, multivariate regression was applied to analyse the integrated impacts of different environmental factors on sleeping environment satisfaction.

Although the conclusions above are obviously observed in this study, more studies for verification are still needed in the future.

5. Acknowledgments

The research was supported by the National Natural Science Foundation of China (No. 51678330) and Volvo Group in a research project of the Research Center for Green Economy and Sustainable Development, Tsinghua University.

6. References

Brink, M. 2011. Parameters of well-being and subjective health and their relationship with residential traffic noise exposure--a representative evaluation in Switzerland. *Environment International,* 37**,** 723-733.

Griefahn, B., Schuemerkohrs, A., Schuemer, R., Moehler, U. & Mehnert, P. 2000. Physiological, subjective, and behavioural responses during sleep to noise from rail and road traffic. *Noise & Health,* 3**,** 59.

Haskell, E. H., Palca, J. W., Walker, J. M., Berger, R. J. & Heller, H. C. 1981. Metabolism and thermoregulation during stages of sleep in humans exposed to heat and cold. *Journal of Applied Physiology Respiratory Environmental & Exercise Physiology,* 51**,** 948.

Huang, L., Zhu, Y., Ouyang, Q. & Cao, B. 2012. A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices. *Building and Environment,* 49**,** 304-309.

K. Kräuchi, C. C., E. Werth, A. Wirz-Justice 2000. Functional link between distal vasodilation and sleep-onset latency?

Kripke, D. F., Elliott, J. A., Youngstedt, S. D. & Rex, K. M. 2007. Circadian phase response curves to light in older and young women and men. *Journal of Circadian Rhythms,* 5**,** 4.

Lan, L., Tsuzuki, K., Liu, Y. F. & Lian, Z. W. 2017. Thermal environment and sleep quality: A review. *Energy and Buildings,* 149**,** 101-113.

Pigeon, W. R. & Grandner, M. A. 2013. Creating an Optimal Sleep Environment. *Encyclopedia of Sleep***,** 72-76.

Pirrera, S., De Valck, E. & Cluydts, R. 2014. Field study on the impact of nocturnal road traffic noise on sleep: the importance of in- and outdoor noise assessment, the bedroom location and nighttime noise disturbances. *Sci Total Environ,* 500-501**,** 84-90.

Pirrera, S., De, V. E. & Cluydts, R. 2010. Nocturnal road traffic noise: A review on its assessment and consequences on sleep and health. *Environment International,* 36**,** 492-498.

Schervish, M. J. 1987. A Review of Multivariate Analysis. *Statistical Science,* 2**,** 396-413.

Siegel, J. M. 2005. Clues to the functions of mammalian sleep. *Nature,* 437**,** 1264.

Song, C., Liu, Y., Zhou, X., Wang, X., Li, J. & Liu, J. 2016. Temperature field of bed climate and thermal comfort assessment based on local thermal sensations. *Building and Environment,* 95**,** 381-390.

The assessment of the environmental quality directly perceived and experienced by the employees of 69 European offices

A. Marchenko[1,*], S. Carlucci[1], L. Pagliano[2], M. Pietrobon[2], T. Karlessi[3], M. Santamouris[3], N. Delaere[4] and Margarita Assimakopoulos[3]

[1] Department of Civil and Environmental Engineering, NTNU Norwegian University of Science and Technology, Trondheim, Norway.
[2] Department of Energy, Politecnico di Milano, Milano, Italia.
[3] Department of Physics, University of Athens, Athens, Greece.
[4] Factor4, Antwerpen, Belgium.
[*] Corresponding author email: alla.marchenko@ntnu.no, phone: (+47) 936 29701

Abstract: A number of scientific studies have shown that the performance capacity and employees' satisfaction, enjoyment and health are directly affected by how building occupants perceive the environmental conditions that characterize their working environment. The physical well-being and comfort perception of employees directly impacts their productivity and satisfaction. However, several researchers have shown that, in numerous office environments, indoor environmental conditions are far from being perceived as comfortable. Often the main causes are faultily commissioned and operated building management systems, the lack of appropriate and coherent quality management procedures and errors in design or construction of the building systems. In order to identify critical conditions and provide a set of improvement measures, a data collection and analysis tool has been developed. It is called *Comfortmeter* and is used, in this paper, to analyze 69 office environments distributed throughout Europe. The tool enables the evaluation of the performance of a building as directly experienced by its occupants. The evaluation covers the themes of thermal, visual and acoustic comfort, indoor air quality, individual control possibilities and the quality of the office environment. It provides detailed outcome and practical advice to create a healthier working environment for employees. In order to use the tool, it is required, first, to administrate an online survey among the employees. Then, the employees' responses are gathered and stored in a database. Next, the stored data are statistically analyzed to objectify the occupants' subjective comfort experience. Finally, a report is generated and presents (i) a comparative analysis of the building performance, (ii) a structured and easy-to-understand overview of the current comfort satisfaction as perceived by occupants, (iii) an indication of possible areas of improvement as well as (iv) a suggestion of the measures necessary to raise the comfort level and, eventually, the occupants' satisfaction and productivity.

Keywords: Thermal comfort, visual comfort, acoustic comfort, indoor environmental quality, post-occupancy evaluation

1. Introduction

Indoor environmental quality (IEQ) and comfort some of the primary needs of a working space because it is the place where people spend most of the time after their own homes. Furthermore, according to the UNEP Sustainable Building and Climate Initiative (SBCI), the most of the building stock which will exist in 2050 has been already built (Sbci, 2009). Therefore, with respect to these circumstances, it is important to develop clever solutions aimed at improving comfort and overall occupants' satisfaction of the built environment without neglecting the need to reduce the use of resources and greenhouse-gas emissions. The variety of the office layouts, approaches to HVAC systems, lighting, furnishing and quality management, together create different degrees of the comfort inside a facility. Various studies (such as (Tanabe et al., 2015, Chadburn et al., 2017, Mulville et al., 2016, Haynes, 2008) and others) show that there is a visible correlation between occupants' comfort at the working space and their productivity.

It is reasonable to believe that open offices tend to have more issues with respect to the comfort perception, space management and resource usage due to the variety of employees who share the offices and their perception of the indoor climate.

This paper provides an evaluation of 69 EU office environments based on the data collected from the developed tool for analysis called *Comfortmeter* in the framework of the European Horizon 2020 QUANTUM project.

1.1. Post-occupancy evaluation of the environmental quality in office buildings

Post-occupancy evaluation (POE) was first mentioned in the 1960s. It was introduced as a remedy from significant problems in the field of building performance (Preiser, 1995). The main advantage of POE is that it can help to eliminate health problems, poor air circulation and other issues related to building operation and use. Because, starting from the moment when the building has been built and occupied for some time (Göçer et al., 2015) and ending by demolition, POE delivers an opportunity to track occupants' satisfaction, indoor environment and outcomes from technical maintenance of the building (Khalil and Husin, 2009). All this information is gained via systematically scheduled questionnaire, surveys (such as the Comfortmeter survey), on-site measurements and interviews. The collected information is processed and the results of the evaluation may be used by the facility manager or any other person who is responsible for building operation.

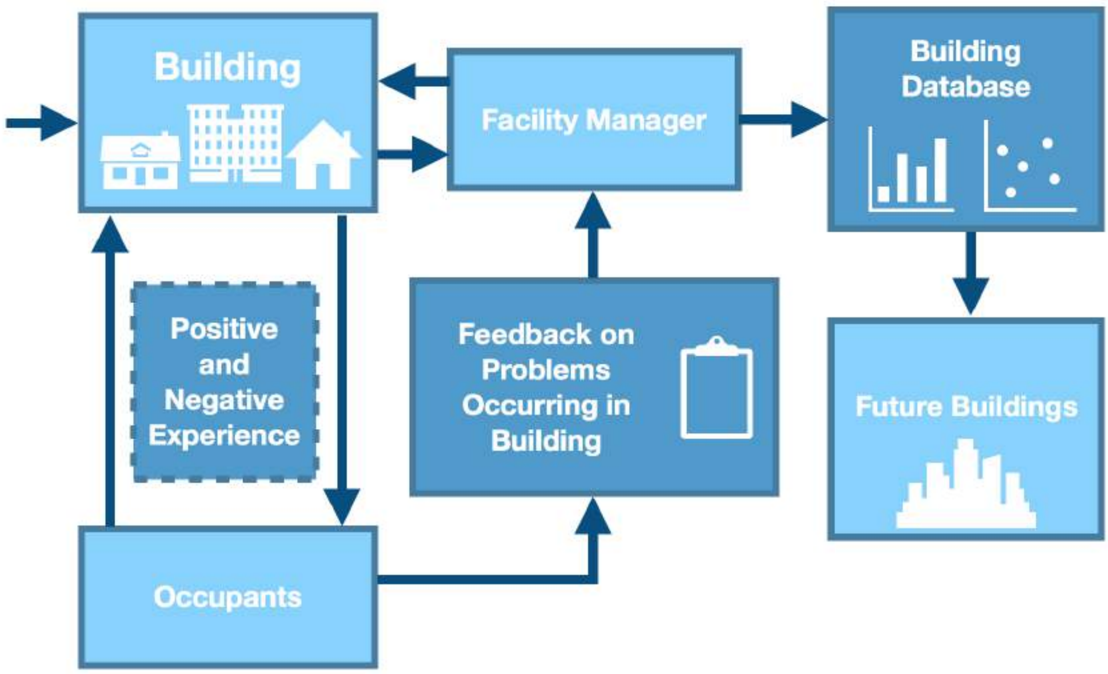


Figure 1 Direct benefits from POE implementation at building facilities

The facility managers (Figure 1) may get a lot of benefits from implementation of POE on a regular basis: feedback from the building occupants provides an opportunity to increase the comfort of the living area (short term benefits), introduction of the feed-forward link between future buildings and operational buildings helps to increase the quality of the future structures (medium term benefit), if occupants' feedback and negative/positive experience are combined in to a database (long term benefit), it may be grounds for future improvements and modeling of building projects (Preiser, 1995). Also, it is possible to use POE results for benchmarking, that in its turn may result in a solid platform for the sustainable development of future construction projects (Göçer et al., 2015).

According to Preiser (1995), POE methodology can be classified into the following approaches: (i) inductive, (ii) investigative, and (iii) diagnostic. In time scale, diagnostic POE is the most time consuming if compared to the other above-mentioned approaches since it may take a month or even years due to high requirements for data accuracy and the wide range of evaluation methods needing to be considered. Inductive POE usually performs fast, as it requires brief data overview and interviews with key persons. Investigative POE is performed in the case when inductive POE has found specific issues which need further investigation. Investigative POE may take up to a few weeks depending on the scale of the building and degree of the problem(s) discovered.

In total, Khalil and Husin (2009) represent schematically a POE application with three sequential phases (Figure 2).

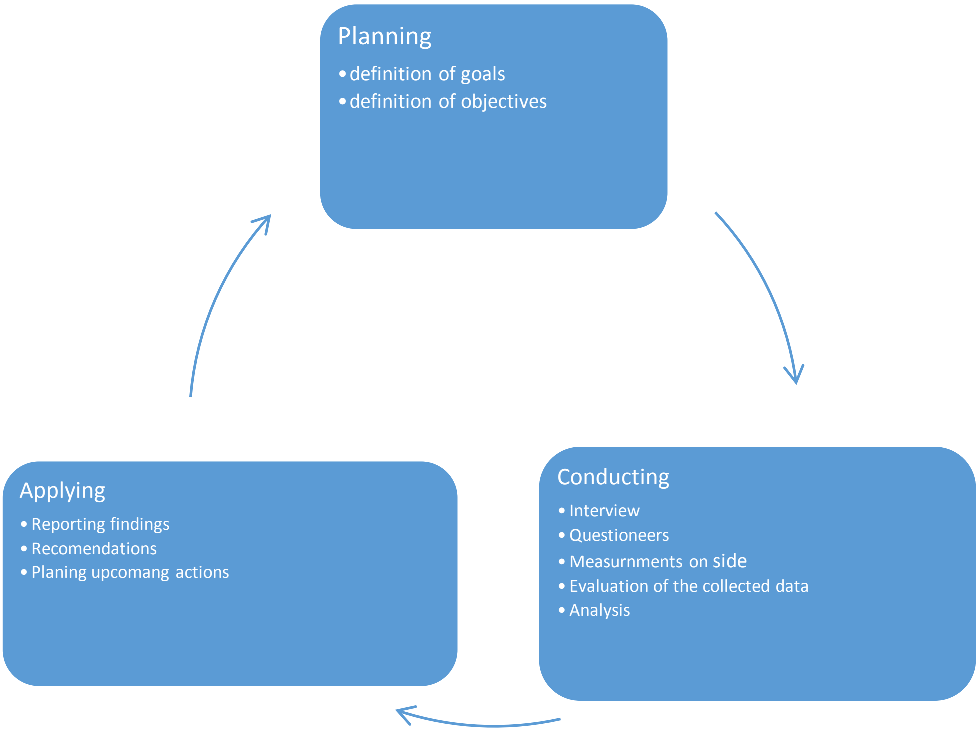


Figure 2 The three phases of the POE cycle

The goal of the POE, and its main objectives and possible outcomes are determined at the planning phase. It is important to determine the main purpose of the investigation (goal), discuss step by step actions and type of the data that should be collected (objectives). Together this is a ground for all investigation and it determines the quality of the achieved results.

The conduction phase associates with data collection. It should be treated carefully with precision and tracking of the inputs from questionnaires, interviews and overall assessment of the building. With this in mind, protected data storage and good architecture of the database are going to provide easy interaction with the information obtained. Since the amount of collected data is usually big, easy to understand acronyms and a logical structure are the keys to straightforward data processing and evaluation without misunderstanding or misinterpretation. This will result in a faster and more precise evaluation process.

The applying phase is the last step in the POE. It includes graphs and tables that present results from the data processing stage. A few options or suggestions for the improvement may be developed based on the outcomes of data processing.

1.2. Measurements of occupants' satisfaction and productivity in offices

The success of any organization is highly dependant on the productivity of its employees. This is an explanation of the variety of studies dedicated to the main components of productivity, and possible approaches and actions to improve it (Clements-Croome, 2006, Al Horr et al., 2016). In general productivity can be defined as the rate of output per unit of input (Al Horr et al., 2016). However, this definition can vary with respect to the industry and company's criteria on productivity calculation (such as management by objectives, quantitative method, measuring sales productivity and many others). That said, comfort at the workplace and satisfaction from the indoor environment are among the key variables which influence employee productivity.

Generally speaking, comfort can be seen as the absence of unpleasant sensations and no trigger to change something in the indoor environment parameters (Hensen and Lamberts, 2012). There are different types of comfort (Figure 3) including physical comfort (e.g., thermal comfort, visual comfort, acoustic, indoor air quality etc.); functional comfort (e.g., distance from work to home, interruptions etc.); psychological comfort (such as privacy, space ownership etc.) (Al Horr et al., 2016).

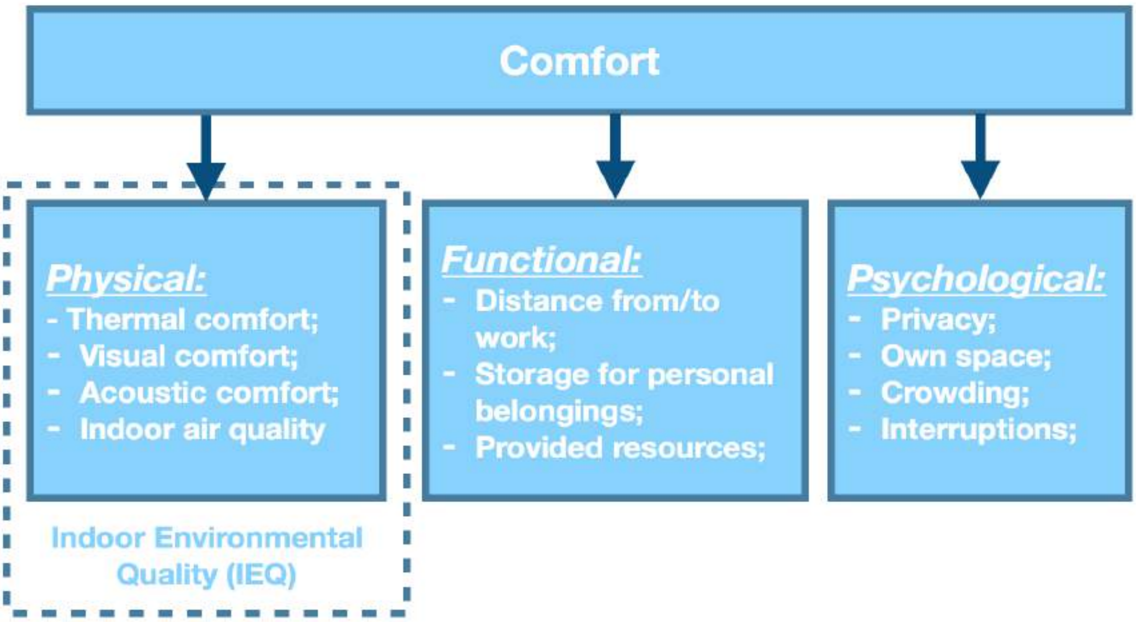


Figure 3 The overview of the main comfort types

Focusing on physical comfort, several methods are available in the literature to assess the performance of a given environment in providing optimal operational conditions for occupants. Several metrics aim at assessing thermal comfort in buildings (Carlucci, 2013, Carlucci and Pagliano, 2012). Furthermore, other metrics may be used to assess a visual environment by evaluating the risk of glare, the amount of light, the light quality of artificial lamps in rendering colors, and the light uniformity (Carlucci et al., 2015). Indeed, elimination of the glare, rational daylight use and illumination are important parameters which need to be well-thought-out during indoor space utilization.

Occupants' perception of the indoor thermal environment is another point to consider. Thermal comfort is assured by the combination of the factors which influence the heat exchange between a person and his/her environment (Croitoru et al., 2015). These factors are predetermined either due to the human body (e.g. age, sex, diet, weight, etc.) or external conditions (e.g. fabrics used for clothes, number of layers, indoor temperature, etc.). Furthermore, thermal comfort may be determined using three different approaches, namely, physiological, psychological and rational (Attia and Hensen, 2014, Enescu, 2017). The physiological approach addresses the thermal perception of humans via the central nervous system and the hypothalamus, where the psychological approach defines thermal comfort, in a general view, as 'a condition of mind that expresses satisfaction with the thermal environment' (Standard, 2004). On the other hand, the rational approach deals with the heat balance of the human body.

Due to the complexity of these phenomena, a number of sensation scales have been developed for the evaluation of personal thermal state (Hensen and Lamberts, 2012). As an example, consider the following scales defined by ISO 10551 (1995): a scale of perception of the personal thermal state, an evaluative scale and a future thermal preference scale (Hensen and Lamberts, 2012, Pagliano and Zangheri, 2010). While the perception scale defines how the person feels at the time he/she is filling out the survey the evaluative scale determines if the actual temperature differs from the comfortable temperature for the person. The future thermal preference scales provide preferences for the future time inside the given space.

On the the other hand, there also exist a set of negative factors, such as high or low air temperature, air speed across body surface, relative humidity, molds, fungi, and etc, that directly impact occupant health, and may result in mucosal, skin irritations, and general symptoms which are temporal and associated with work in particular buildings (Burge, 2004, Crook and Burton, 2010). In the literature, this phenomenon is usually referred to as Sick Building Syndrome (SBS) (Kubba, 2009). Main symptoms of SBS are: nausea, eye irritation, throat irritation, a runny nose, dry skin and so forth (Shan et al., 2016). As a consequence, SBS may result in low productivity among employees, angry behaviour, irritation, depression and often a rise in sick leave(s) (Lim et al., 2015, Beck, 1979). While, symptoms' intensity may vary due to geographical location and climate zones, the approach for SBS detection and tracking remain the same. Among crucial actions in SBS prevention, holding surveys among employees, having regular measurements of indoor conditions, and checking mold formation could be named (Gunnarsson, 2000, Runeson et al., 2006).

1.3. About QUANTUM

The research presented here was developed within the wider research program originated by the European project entitled *Quality management for building performance – Improving energy performance by life cycle quality management* (Quantum) started on 01/01/2016 and ending on 31/12/2019. This research project focuses on the development and demonstration of quality management tools with high replication potentials for building performance in the design, construction, commissioning and operation phases as a means to narrow down the performance gap between predicted and actual energy performance in European buildings.

Furthermore, it is expected that those tools can improve health aspects and user satisfaction while reducing environmental impact.

2. Methodology

A number of scientific studies have shown that the performance capacity and employee satisfaction, enjoyment and health are directly affected by how building occupants perceive the environmental conditions that characterize their working environment. The physical well-being and comfort perception of employees directly impacts their productivity and satisfaction. However, several researchers have shown that, in numerous office environments, indoor environmental conditions are perceived as far from comfortable. Often the main causes are faultily commissioned and operated building management systems, the lack of appropriate and coherent quality management procedures and errors in design or construction of the building systems. In order to identify critical conditions and provide a set of improvement measures, a data collection, and analysis tool has been developed. It is called *Comfortmeter* and is a post-occupancy evaluation tool that is specifically designed for use in office buildings. This tool consists of a survey, a statistical analysis of occupants' responses, and visualization of the analysis outcomes.

The survey does not require an on-site visit nor any software installation on users' computers. It is an online survey accessible with a standard web-browser and is administered via email. Reminders can be enabled to increase the response rate. The online survey investigates the performance of a building through its daily users. It covers comfort-related topics with over 55 questions and documents the performance of the building in respect of thermal, visual and acoustic comfort, indoor air quality, individual control possibilities and the office environment.

After completing the survey, data gathered through the survey undergoes a quality check and then is stored in a database. Next, a user-anonym statistical analysis is carried out on the data stored in the database to objectify the subjective comfort experience of building occupants through an econometric model.

The outcome of the statistical analysis contains detailed and practical advices to create a healthier workplace environment for the building's employees. Specifically, the outcomes are drawn in a report that includes the current satisfaction within the building, the areas of improvement, the measures necessary to for raising the comfort level as well as a quantitative estimation of the impact of the building comfort level score on the employees' productivity. Moreover, a comparison of the analyzed building performance contrasted against the aggregated performance of other and similar previously analyzed office buildings. In summary, the outcomes offer a structured overview of the productivity and comfort satisfaction of the employees working in the building.

3. The statistical analysis and results

Throughout the duration of the task, it was possible to survey 1421 employees with different backgrounds, age and social status. Offices in EU and Scandinavian countries (Figure 4) took part in the Comfortmeter surveys and got feedback on their indoor environment status.

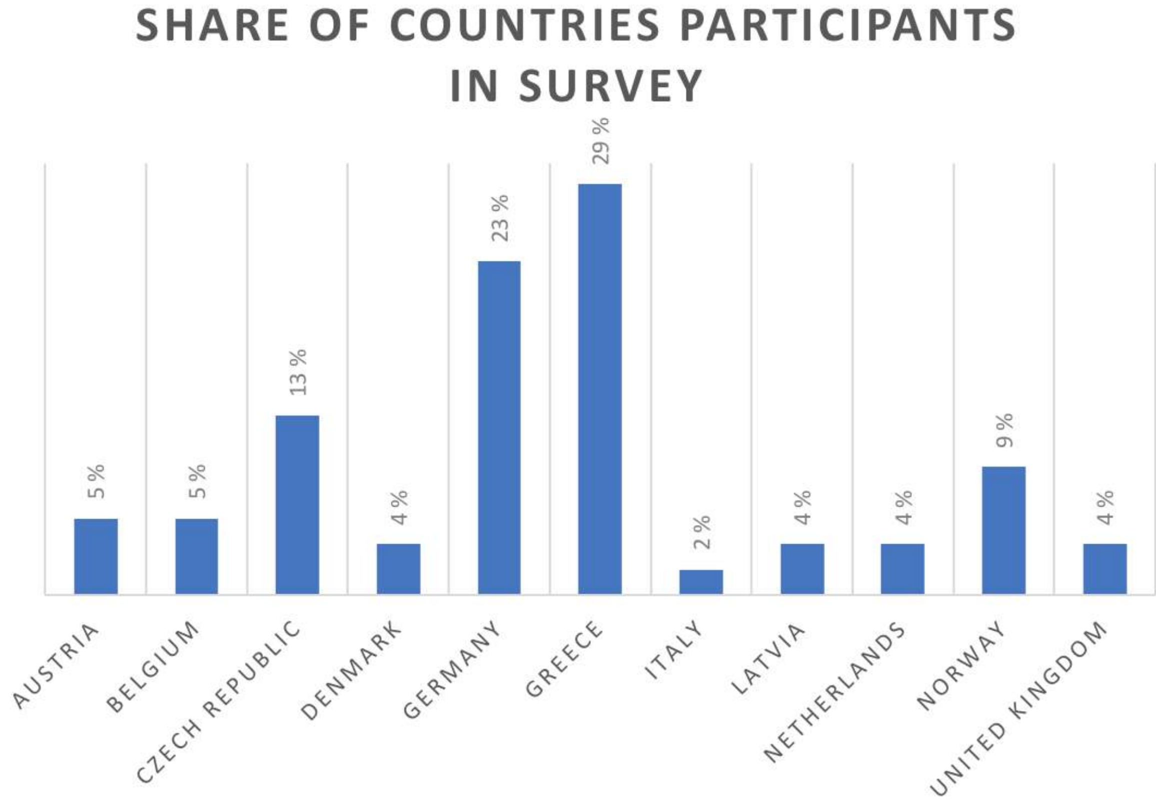


Figure 4 Share of countries participants in survey

Generally, the database has 48% of responses from female and 52% from male employees. This gives a good opportunity to see the difference in perception of the office environment by sex. Data on age is also available and can be seen in Figure 5.

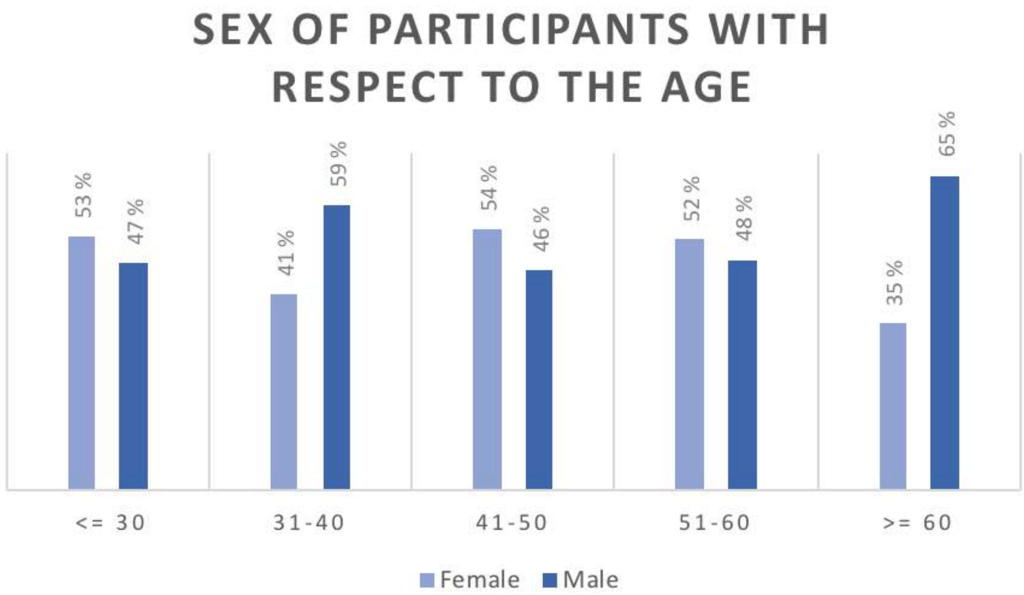


Figure 5 Sex of participants with respect to the age

Since POE is important for the generation of the building profile database, it is important to involve people who have worked in the building for at least the previous 12 months in order to provide a more accurate profile of the indoor environment. Figure 6 presents gathered data on the amount of time employees have been working in the office.

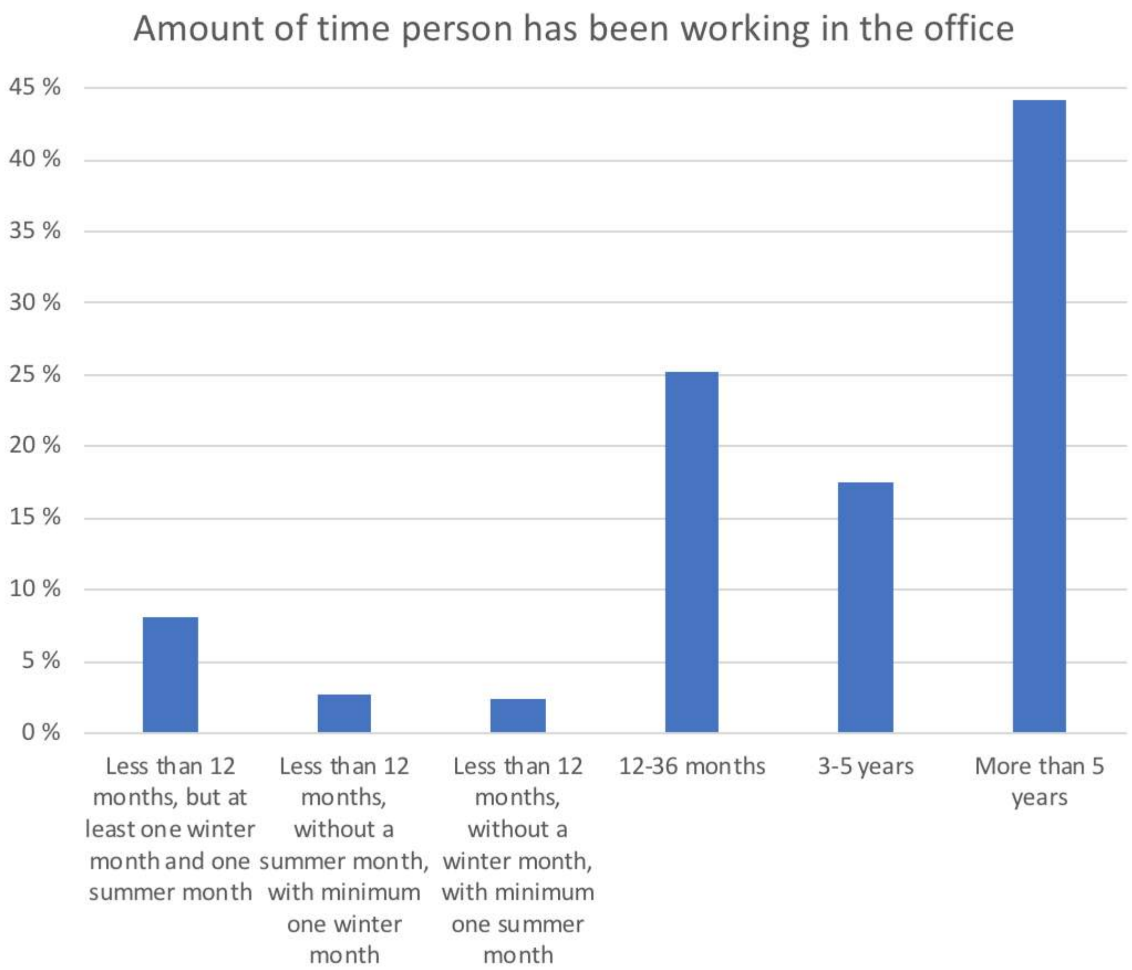


Figure 6 Amount of time person has been working in the office

Since people also have a degree of the responsibility for their indoor comfort, the ability to adapt clothes to the office conditions is another important factor of concern. A detailed overview of the data on ability to adapt clothes to indoor conditions with respect to the gender and age can be observed in Figure 7. But some offices have a specific dress code which will prevent occupants adapting or performing any changes.

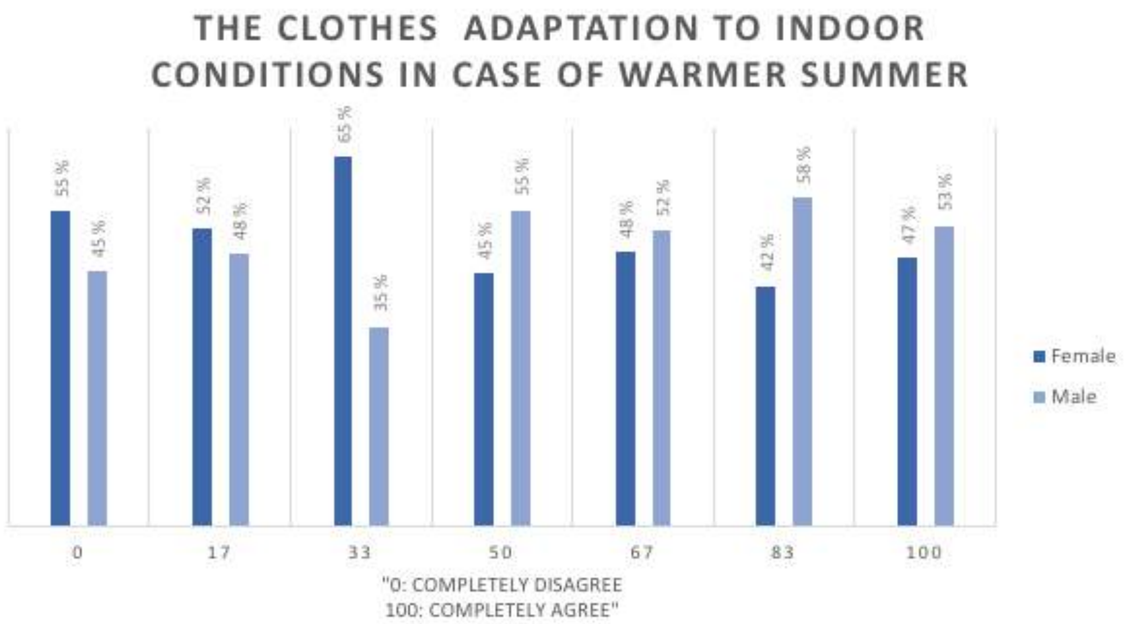


Figure 7 The clothing adaptation in case of warmer summer with respect to the sex and age

Survey data on the degree of the overall satisfaction from the office indoor environment with respect to each individual response showed that the following categories "cleanliness and maintenance of your working space", "amount of light and visual comfort" and "office layout, office furniture, window view etc." have the highest rank of satisfaction among employees.

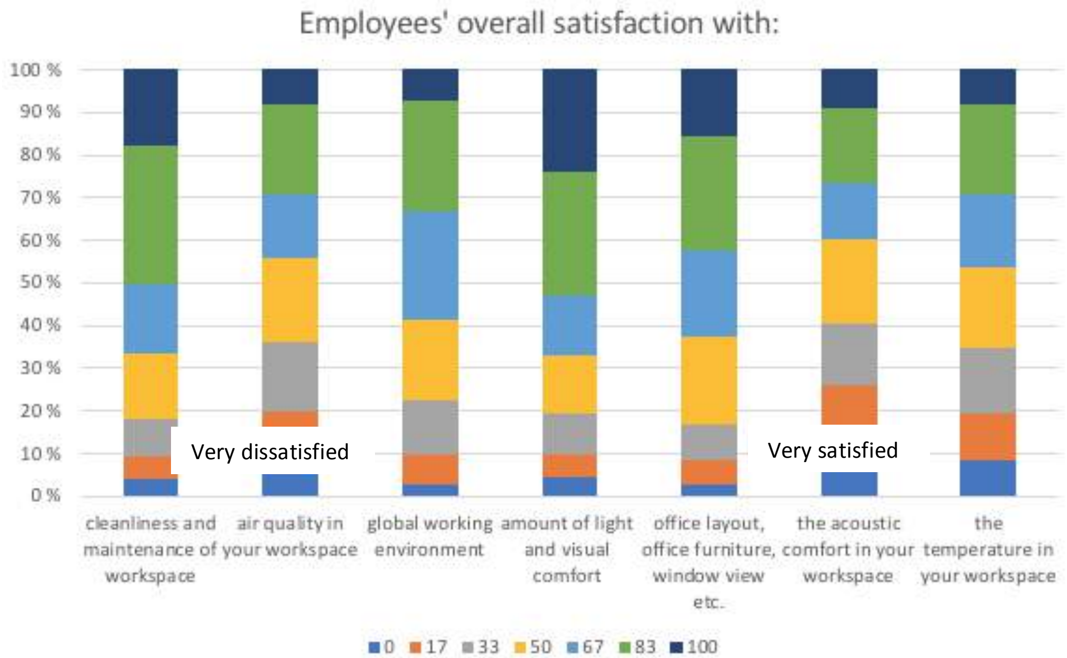


Figure 8 The overall satisfaction from the working space

SPSS statistic software package was used to perform Kruskal-Wallis test in order to analyze variance between independent categorical variable "Age" and number of dependent variables shown at Table 1. The Kruskal-Wallis test reviled a statistically significant difference in indoor satisfaction level across the five different age groups $Gp1: \leq 30, n = 362; Gp2: 31 - 40, n = 405; Gp3: 41 - 50, n = 306; Gp4: 51 - 60, n = 244; Gp5 \geq 60, n = 104$ for the following cases 1, 2, 5, 6, 11, 13, 14, 22 and 23 (see Table 1).

Table 1 Results from the Kruskal-Wallis Test

№	Dependent variables	Age		
		Asymp. Sig.	Age (highest/lowest overall ranking)	
1	The general air quality	0,009	[>= 60]	[<= 30; 31-40; 41-50; 51-60]
2	Clothes adaptation to the warmer conditions	0,011	[31-40; 41-50]	[<= 30; 51-60; >= 60]
3	Overall Satisfaction with cleanness of the office	0,267	[-]	[-]
4	Possibility to regulate the cooling in office	0,547	[-]	[-]
5	Possibility to regulate the heating in office	0,0000209	[31-40; 41-50; 51-60; >= 60]	[<= 30]
6	Possibility to regulate the lighting in office	0,0000139	[31-40; 41-50; >= 60]	[<= 30; 51-60]
7	Overall possibility to regulate environment conditions inside office	0,303	[-]	[-]
8	Overall satisfaction from the working environment	0,529	[-]	[-]
9	Extent to which global working environment affect your productivity	0,709	[-]	[-]
10	Amount of light at workplace	0,384	[-]	[-]
11	The sufficient amount of daylight	0,044	[>= 60]	[<= 30; 31-40; 41-50; 51-60]
12	Overall satisfaction from the amount of light and visual comfort	0,847	[-]	[-]
13	Satisfaction from the office furniture	0,0000525	[41-50; >= 60]	[<= 30; 31-40; 51-60]
14	Office layout	0,004	[41-50; 51-60; >= 60]	[<= 30; 31-40]
15	The overall outdoor appearance of the building	0,451	[-]	[-]
16	Satisfaction from the office layout	0,075	[-]	[-]
17	View from the window	0,387	[-]	[-]
18	In general, my health is good	0,161	[-]	[-]
19	Overall satisfaction from acoustic comfort	0,438	[-]	[-]
20	The sound privacy	0,280	[-]	[-]
21	Overall satisfaction with the temperature	0,059	[-]	[-]
22	In the summer, it is never too warm in my workspace	0,00000207	[>= 60]	[<= 30]
23	In the winter, it is never too warm in my workspace	0,007	[>= 60]	[<= 30; 31-40; 41-50]

(red)	No statistically significant difference
(green)	Statistically significant difference

<u>Case 1</u> “Satisfaction with general air quality inside the office”: the older age group $Gp5 \geq 60$ recorded higher median score (Md = 67) than other groups. $Gp1: \leq 30$, $Gp2: 31 - 40$, $Gp3: 41 - 50$ and $Gp4: 51 - 60$ got lower median score (Md = 50).

<u>Case 2</u> “Possibility for clothes adaptation to the warmer conditions”: $Gp2: 31 - 40$ and $Gp3: 41 - 50$ recorded higher median score (Md = 83) than other groups. $Gp1: \leq 30$, $Gp4: 51 - 60$ and $Gp5 \geq 60$ got the lowest median score (Md = 67).

<u>Case 5</u> “Possibility to regulate the heating in the office”: $Gp2: 31 - 40$, $Gp3: 41 - 50$, $Gp4: 51 - 60$ and $Gp5 \geq 60$ recorded higher median score (Md = 50) than other groups. $Gp1: \leq 30$ got the lowest median score (Md = 33).

<u>Case 6</u> “Possibility to regulate the lighting in the office”: $Gp2: 31 - 40$, $Gp3: 41 - 50$ and $Gp5 \geq 60$ recorded the higher median score (Md = 83). $Gp1: \leq 30$ and $Gp4: 51 - 60$ got the lowest median score (Md = 67).

Case 11 "The sufficient amount of the daylight": $Gp5 \geq 60$ recorded higher median score (Md = 91) than other groups. $Gp1: \leq 30, Gp2: 31-40, Gp3: 41-50$, and $Gp4: 51-60$ got the lowest median score (Md = 83).

Case 13 "Satisfaction form the office furniture": $Gp3: 41-50$ and $Gp5 \geq 60$ recorded higher median score (Md = 83) than other groups. $Gp1: \leq 30$, $Gp2: 31-40$ and $Gp4: 51-60$ got the lowest median score (Md = 67).

Case 14 "Office layout": $Gp3: 41-50$, $Gp4: 51-60$ and $Gp5 \geq 60$ recorded higher median score (Md =83) than other groups. $Gp1: \leq 30$ and $Gp2: 31-40$ got the lowest median score (Md = 67).

Case 22 "In the summer it is never to worm in my workplace": $Gp5 \geq 60$ recorded higher median score (Md =67) than other groups. $Gp1: \leq 30$ got the lowest median score (Md = 41).

Case 23 "In the winter it is never too warm in my workplace": $Gp5 \geq 60$ recorded higher median score (Md =83) than other groups. $Gp1: \leq 30$, $Gp2: 31-40$ and $Gp3: 41-50$ got the lowest median score (Md = 67).

4. Discussion and conclusions

The Comfortmeter is a tool used in the framework of EU project QUANTUM. It has been in operation for a few years already and the creators are working constantly on its improvement in order to deliver knowledge to society. As was highlighted in the previous sections, indoor comfort is a complex term since it is highly dependdent on the age and sex of the person, their background, ethnicity, habits and many more. Given circumstances precede a need for a complex approach in order to improve working environment and as result to increase productivity and satisfaction from the interaction within an indoor space. The Comfortmeter may be used not only to understand a degree of the comfort at the workplace and improve conditions when needed but also for post-occupancy evaluation because it provides an opportunity to create and accumulate knowledge based on previous actions and outcomes.

The survey held in 11 countries provided 1421 responses which are highly beneficial for the future building projects and renovation actions. The gathered database provided insights on such important phenomena as the perception of the comfort of the working environment with respect to the age and gender. Furthermore, the Kruskal-Wallis test revealed statistically significant difference in indoor satisfaction level across the five different age groups Gp1:≤30,n=362; Gp2: 31-40,n=405; Gp3: 41-50,n=306; Gp4:51-60,n=244; Gp5 ≥60,n=104 for the following cases 1, 2, 5, 6, 11, 13, 14, 22 and 23. As result it is possible to conclude that there is a visible connection between age and ability to pursue comfort and adapt to changes.

5. Acknowledgments

This work was funded by the European Union's Horizon 2020 Research and Innovation Programme under grant agreement 680529, acronym QUANTUM. The sole responsibility for the content of this article lies with the authors. It does not necessarily reflect the opinion of the European Commission (EC). The EC is not responsible for any use that may be made of the information this article contains.

The authors wish to thank all the participants of both Annex 66 entitled *Definition and Simulation of Occupant Behavior in Buildings*, and Annex 69 entitled *Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings* for the sharing of experiences and the inspiring discussions.

6. References

Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Katafygiotou, M. & Elsarrag, E. 2016. Occupant productivity and office indoor environment quality: A review of the literature. *Building and Environment,* 105, 369-389.

Attia, S. & Hensen, J. L. Investigating the impact of different thermal comfort models for zero energy buildings in hot climates. Proceedings 1st Int. Conf. on Energy and Indoor Environment for Hot Climates, 2014.

Beck, A. T. 1979. *Cognitive therapy of depression*, Guilford press.

Burge, P. 2004. Sick building syndrome. *Occupational and environmental medicine,* 61, 185-190.

Carlucci, S. 2013. *Thermal Comfort Assessment of Buildings,* London, Springer.

Carlucci, S., Causone, F., De Rosa, F. & Pagliano, L. 2015. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. *Renewable and sustainable energy reviews,* 47, 1016-1033.

Carlucci, S. & Pagliano, L. 2012. A review of indices for the long-term evaluation of the general thermal comfort conditions in buildings. *Energy and Buildings,* 53, 194-205.

Chadburn, A., Chadburn, A., Smith, J., Smith, J., Milan, J. & Milan, J. 2017. Productivity drivers of knowledge workers in the central London office environment. *Journal of Corporate Real Estate,* 19, 66-79.

Clements-Croome, D. 2006. *Creating the productive workplace*, Taylor & Francis.

Croitoru, C., Nastase, I., Bode, F., Meslem, A. & Dogeanu, A. 2015. Thermal comfort models for indoor spaces and vehicles—Current capabilities and future perspectives. *Renewable and Sustainable Energy Reviews,* 44, 304-318.

Crook, B. & Burton, N. C. 2010. Indoor moulds, sick building syndrome and building related illness. *Fungal Biology Reviews,* 24, 106-113.

Enescu, D. 2017. A review of thermal comfort models and indicators for indoor environments. *Renewable and Sustainable Energy Reviews,* 79, 1353-1379.

Göçer, Ö., Hua, Y. & Göçer, K. 2015. Completing the missing link in building design process: Enhancing post-occupancy evaluation method for effective feedback for building performance. *Building and Environment,* 89, 14-27.

Gunnarsson, A. G. 2000. Relationships between occupant personality and the sick building syndrome explored. *Indoor Air,* 10, 152-169.

Haynes, B. P. 2008. Impact of workplace connectivity on office productivity. *Journal of Corporate Real Estate,* 10, 286-302.

Hensen, J. L. & Lamberts, R. 2012. *Building performance simulation for design and operation*, Routledge.

Khalil, N. & Husin, H. N. 2009. Post occupancy evaluation towards indoor environment improvement in Malaysia's office buildings. *Journal of Sustainable Development,* 2, 186.

Kubba, S. 2009. *LEED practices, certification, and accreditation handbook*, Butterworth-Heinemann.

Lim, F.-L., Hashim, Z., Said, S. M., Than, L. T.-L., Hashim, J. H. & Norbäck, D. 2015. Sick building syndrome (SBS) among office workers in a Malaysian university—Associations with atopy, fractional exhaled nitric oxide (FeNO) and the office environment. *Science of the Total Environment,* 536, 353-361.

Mulville, M., Mulville, M., Callaghan, N., Callaghan, N., Isaac, D. & Isaac, D. 2016. The impact of the ambient environment and building configuration on occupant productivity in open-plan commercial offices. *Journal of Corporate Real Estate,* 18, 180- 193.

Pagliano, L. & Zangheri, P. 2010. Comfort models and cooling of buildings in the Mediterranean zone. *Advances in Building Energy Research,* 4, 167-200.

Preiser, W. F. E. 1995. Post-occupancy evaluation: how to make buildings work better. *MOB Univarcity Press,* 13, 19-28.

Runeson, R., Wahlstedt, K., Wieslander, G. & Norbäck, D. 2006. Personal and psychosocial factors and symptoms compatible with sick building syndrome in the Swedish workforce. *Indoor air,* 16, 445-453.

Sbci, U. 2009. Buildings and climate change: Summary for decision- makers. *United Nations Environmental Programme, Sustainable Buildings and Climate Initiative, Paris*, 1-62.

Shan, X., Zhou, J., Chang, V. W.-C. & Yang, E.-H. 2016. Comparing mixing and displacement ventilation in tutorial rooms: Students' thermal comfort, sick building syndromes, and short-term performance. *Building and Environment,* 102, 128-137.

Standard, A. 2004. Standard 55-2004. *Thermal environmental conditions for human occupancy*, 9-11.

Standardization, I. O. F. 1995. *Ergonomics of the Thermal Environment: Assessment of the Influence of the Thermal Environment Using Subjective Judgement Scales*, ISO.

Tanabe, S.-I., Haneda, M. & Nishihara, N. 2015. Workplace productivity and individual thermal satisfaction. *Building and Environment,* 91, 42-50.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

A real-world empirical investigation of indoor environment and workplace productivity in a naturally-ventilated office environment

Rajat Gupta[1] and Alastair Howard[1]

[1] Low Carbon Building Group, Oxford Institute of Sustainable Development, Oxford Brookes University, UK, rgupta@brookes.ac.uk

Abstract: Most studies on indoor environments and productivity in buildings have been conducted in controlled, static conditions often not representative of the real world, and have used self-reported assessments of productivity. This paper uses a case study-based, real-world approach to empirically investigate the relationship between the indoor environment and workplace productivity in a naturally-ventilated office environment in central London. A range of environmental parameters (indoor temperature, relative humidity (RH) and CO_2) were monitored continuously, alongside outdoor temperatures and RHs for six months covering both heating and non-heating periods. Transverse (BUS survey) and longitudinal surveys (Online survey) recorded occupant perceptions of their working environments, thermal comfort and *self-reported* productivity, while *performance tasks* were designed to *objectively* measure productivity over time in various environmental conditions. Statistical analysis of the data shows that mean indoor temperatures were more strongly correlated with mean outdoor temperatures in the non-heating season (May-July) when compared to the heating season (Feb-Apr), probably due to opening of windows. Indoor RH was found to be low (<30%) while CO_2 levels were high in the heating season (peaks >2500ppm, higher diurnal ranges, higher daily averages). Results from online surveys showed that productivity was reported to decrease when there was an increase in mean indoor temperature and CO_2 levels. Negative but weak correlations were found between the performance task scores and CO_2 levels. Insights from the study can be used to optimise indoor office environments to improve staff productivity.

Keywords: productivity, office, indoor environment, survey, comfort

1. Introduction

Workplace productivity describes how well resources are used to achieve a goal (British Council for Offices, 2017). Research suggests that productivity benefits of 2-3% could be gained by improving the working environment (*ibid.*). When the majority of an organisation's costs relate to its staff, the importance of improving productivity becomes clear. Conversely, poor health and sickness cost UK employers more than £9 billion a year through absenteeism alone (ONS 2014), while presenteeism costs associated with low productivity could be even greater. Some poor health outcomes have been associated with spending prolonged periods of time in office environments with ill effects including musculoskeletal complications (Coggon et al., 2013), cardiovascular disease (Smith et al., 2016), and sick building syndrome (Shahzad et al., 2017). Improvements to office environments should both reduce the cost to employers and improve the health, wellbeing and productivity of employees.

Certain indoor environmental quality (IEQ) parameters in office buildings have been shown to influence workers' productivity (Alker et al., 2015, and references therein). However, there are currently no clearly defined parameters to guide the optimisation of indoor conditions in a range of office environments. The majority of the intervention and office-based studies that have shown increased productivity from improved indoor environment have focussed on individual indoor environment elements, e.g. temperature or ventilation rates (Niemelä et al. 2002; Seppänen et al. 2006; Park & Yoon 2011). However, these do not reflect the dynamic real office settings which experience varying temperature, relative humidity (RH), ventilation rates, and air pollutants over the course of a day. Interpreting data collected in office environments has additional challenges, such as isolating the effects of temperature from air quality; daylighting from outside views; and beneficial background noise versus distracting noise which impacts on workflow and concentration. In addition, office design, layout, and biophilia have all been shown to influence productivity and interact with indoor environment variables controlled by building services (Browning, 2016).

This paper empirically investigates the relationship between indoor environment and productivity in a naturally-ventilated office building in Central London (UK), over six months covering both heating and non-heating periods. A range of indoor environment parameters (temperature, relative humidity (RH) and CO_2 levels) were monitored using data loggers, along with outdoor temperature and RH. *Occupant surveys* were used to estimate self-reported productivity, thermal comfort and perception of working environment, while *performance tasks* were used to objectively assess the productivity of staff. The research study is part of an EPSRC funded *Whole Life Performance Plus* (WLP+) project that seeks to develop a dynamic approach for improving workplace productivity by optimising the indoor environmental conditions.

2. Evidence to date

CEN standard EN15251 acknowledges that the indoor environment affects occupant productivity, health and comfort (CEN, 2007). Recommended limits were therefore set for optimum performance. Negative factors in relation to productivity were often more obvious than positive factors: an environment that is too hot, too cold or too noisy can be uncomfortable or distracting to work in, and finding the optimal level of indoor environment parameters where productivity begins to increase, was found to be more challenging. This is why recent studies, outlined in Table 1, have been seeking to develop an understanding of the relationship between indoor environment and workplace productivity. However, most of these were conducted in climate chambers that create artificial environments.

The effect of temperature on health and comfort has been widely researched and it is broadly recognised as an important indoor environment factor. The recommended limits for Category II mechanically ventilated office buildings are 20-26°C, implying that between 21-25°C there are no direct risk to occupants' health and comfort. For naturally ventilated buildings, comfort indoor temperature is dependent on outdoor temperature and has a much wider comfort band. It is found that indoor temperature significantly influences workers' productivity in the recommended ventilation rate (Tham, 2004) and in a quiet environment (Witterseh et al, 2004). Fang et al. (2004) identified a link between temperature, RH and performance at different ventilation rates (with participants allowed to adjust clothing levels to maintain thermal comfort). At 10l/s/person, difficulty in thinking and other SBS symptoms was highest in 26°C and lowest in 20°C, although no significant effects of indoor environment on the tasks performed could be demonstrated. Lan et al (2011) took 12 participants in the same clothing level, in neutral and warm thermal conditions, and found that performance in all tasks (with the exception of text typing) decreased in warmer conditions. With text typing, although more characters were typed at higher temperature, more errors were also made. The results from the study imply that optimum thermal comfort and optimum productivity may not occur at the same temperatures – a finding supported by others (Al Horr et al., 2016). Seppänen et al's (2006) meta-analysis suggests the temperature range for optimum performance is close to the optimum range for comfort, particularly for mechanically ventilated buildings in winter. In free-running buildings there will be a bigger difference between optimal temperatures for comfort and performance. A 2% decrease in productivity for going 1°C beyond the optimal range will have significant cost implications for the organisation.

An indoor CO_2 concentration upper limit of 1500ppm is specified for office spaces in order to maintain comfort air quality. In studies by Allen et al. (2015), Satish et al. (2012) and Kajtar et al. (2003), performance was found to decrease as CO_2 concentration was increased. These studies indicate every-day CO_2 levels within the current recommended standards can have significant negative impacts on worker performance.

Table 1. Summary of selected, recent studies (intervention and observational) that investigate the links between indoor environment parameters on workplace performance.

Study	Study type and location	Procedure	Results
Tham (2004)	Intervention study in a mechanically ventilated call centre in Singapore (n=56)	Investigated the effect of temperature and ventilation rate.	Reduction in call talk time when ventilation rate was increased. Increase in call talk time when temperature was reduced.
Fang et al (2004)	Intervention study in a mechanically ventilated office in Denmark (n=30)	Participants exposed to different combinations of temperature, RH and ventilation rates.	Increase in SBS symptoms and difficulty in thinking in higher temperature. No significant effect of temperature and humidity on performance
Vimalanathan and Babu (2014)	Intervention study in a climate chamber India (n=10)	Participants exposed to three different thermal conditions and three different light conditions.	Temperature and light account for significant variation in performance.
Lan et al (2011)	Intervention study in a mechanically ventilated office in Denmark (n=12)	Participants exposed to two different thermal conditions (22°C and 30°C).	Performance in eight out of nine tasks (typical of office work) decreased in high temperature.
Seppänen et al (2006)	Review of studies	Meta-analysis conducted on published studies which have investigated the influence of temperature on performance.	Between 21-25°C there is no effect on performance. Updated analysis showed that the temperature range for maximum performance was 21-24°C. Linear model gives a 2% decrease in performance per 1°C increase in temperatures above 25°C.
Satish et al (2012)	Intervention study in a climate chamber in the USA (n=22)	Participants were exposed to different CO_2 concentrations.	Relative to 600ppm, there were moderate to large decrease in decision making performance at 1000ppm and 2500ppm

More recently Innovate UK's national research programme on building performance evaluation (BPE) undertook case study investigations of 50 low energy non-domestic buildings located across the UK, measuring the performance of building fabric, energy consumption, environmental conditions and occupant satisfaction. Meta-analysis of the surveys showed that occupant surveys in 12 out of the 21 workspaces reported an increase in perceived productivity due to the environmental conditions perceived by the occupants (Gupta et al, 2016). The meta-study found that when occupants were satisfied with the indoor temperature, noise, lighting and building related features, perceived productivity increased, while on the other hand, when indoor air was perceived as stuffy and smelly, perceived productivity decreased.

It is evident that there is growing recognition of some kind of a link between indoor environment and perceived productivity in workplaces. This paper seeks to empirically quantify this link between indoor environment, thermal comfort, and perceived and measured productivity, in a central London office environment.

3. Methods and overview of the case study

The methodology adopted in the study has a three-pronged approach: (1) *Physical monitoring of indoor and outdoor environment using data loggers* (2) *Occupant survey (transverse and longitudinal)* and (3) *Performance tasks (productivity tests).* These methods were implemented over a period of six months from 1 February 2017 to 31 July 2017. Figure 1 illustrates the methodological approach adopted in the project.

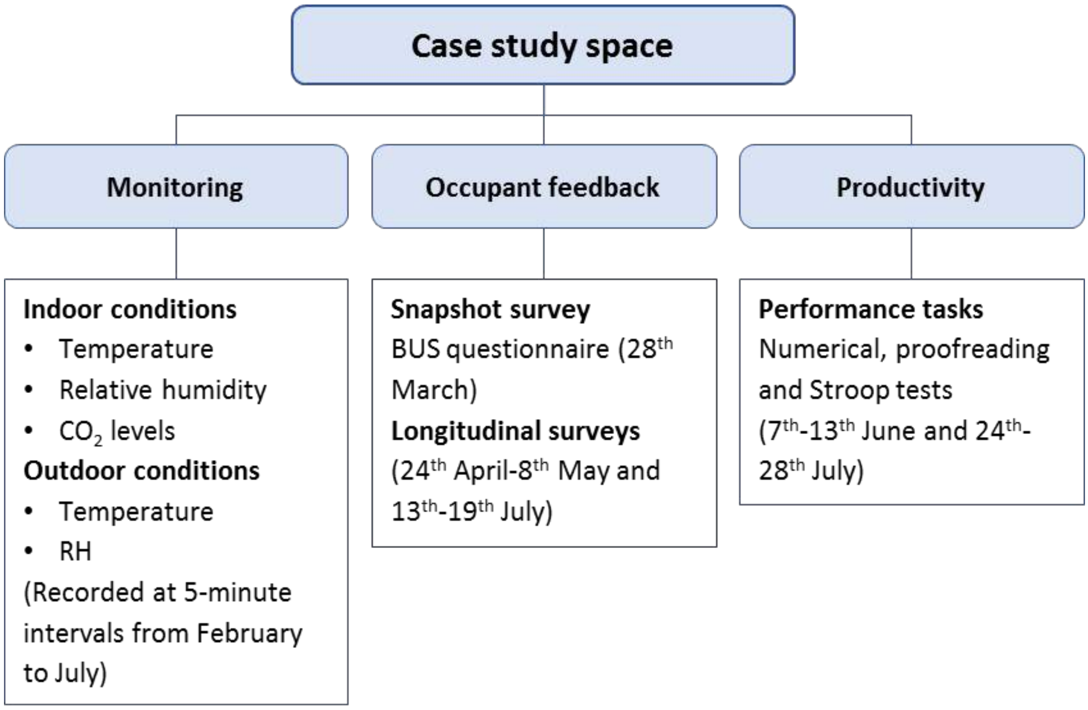


Figure 1. Methodological framework showing duration of physical monitoring, surveys and performance tasks.

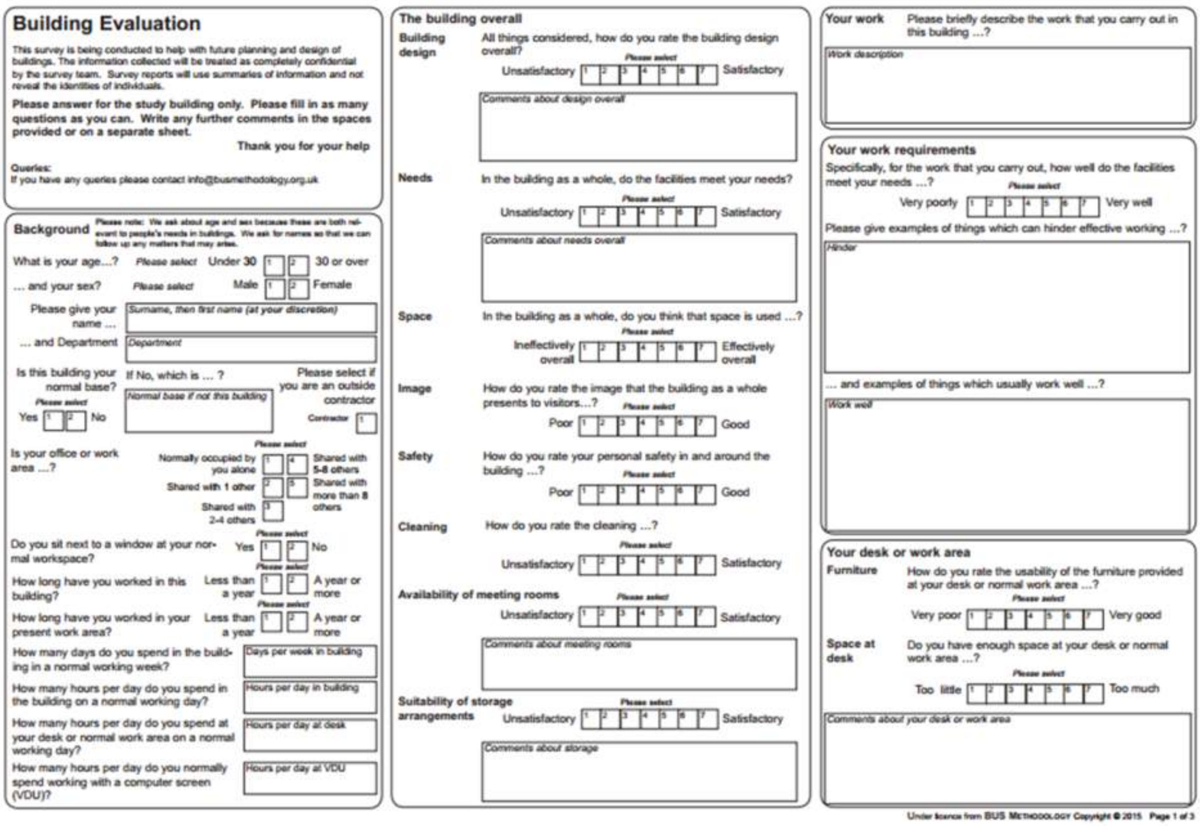
Indoor environmental parameters (temperature, RH and CO_2 levels) and outdoor environmental parameters (temperature and RH) were recorded at five-minute intervals and assessed in daily and hourly profiles for the occupied period. Data logging devices were chosen for physical monitoring due to their appropriate range, good level of accuracy and resolution. Hobo U12's (temperature/RH) and Tinytag TGE-0011's (CO_2) were used internally, and Hobo U23 Pro v2's (temperature/RH) were used externally (specifications given in Table 2). Readings were taken at 5-minute intervals and data manually collected from the loggers on a monthly basis.

Table 2. Specification, resolution and accuracy of data loggers

Device	Parameter	Range	Accuracy	Resolution
Hobo U12	Temperature	-20° to 70°C	±0.35°C	0.03°C
	RH	5% to 95%	±2.5%	0.05%
Tinytag TGE-0011	CO_2	0-5000ppm	± (50ppm +3% of reading)	0.1ppm
Hobo U23 Pro v2	Temperature	-40° to 70°C	±0.21°C	0.02°C
	RH	0-100%	±2.5%	0.03%

Occupant surveys and performance tasks were time stamped so that perceived environment, self-reported (perceived) and measured productivity could be assessed against actual environmental conditions.

The Building User Survey (BUS) provided a snapshot record of occupant perception of their working environment during summer and winter (BUS Methodology, 2018). BUS is a well-established way of benchmarking levels of occupant satisfaction within buildings against a large database of results for similar buildings. The survey uses a structured questionnaire containing 45 questions to record feedback on aspects including thermal comfort and ventilation, lighting and noise, personal control over the environment and change in perceived productivity. The BUS survey was conducted as a paper-based questionnaire in March 2017.



Building Evaluation

This survey is being conducted to help with future planning and design of buildings. The information collected will be treated as completely confidential by the survey team. Survey reports will use summaries of information and not reveal the identities of individuals.

Please answer for the study building only. Please fill in as many questions as you can. Write any further comments in the spaces provided or on a separate sheet.

Thank you for your help

Queries:
If you have any queries please contact info@busmethodology.org.uk

Background — Please note: We ask about age and sex because these are both relevant to people's needs in buildings. We ask for names so that we can follow up any matters that may arise.

What is your age...? *Please select* Under 30 [1] [2] 30 or over

... and your sex? *Please select* Male [1] [2] Female

Please give your name ... *Surname, then first name (at your discretion)*

... and Department *Department*

Is this building your normal base? *Please select* Yes [1] [2] No — If No, which is ... ? *Normal base if not this building* — Please select if you are an outside contractor: Contractor [1]

Is your office or work area ...? *Please select* Normally occupied by you alone [1]; Shared with 1 other [2]; Shared with 2-4 others [3]; Shared with 5-8 others [4]; Shared with more than 8 others [5]

Do you sit next to a window at your normal workspace? *Please select* Yes [1] [2] No

How long have you worked in this building? *Please select* Less than a year [1] [2] A year or more

How long have you worked in your present work area? *Please select* Less than a year [1] [2] A year or more

How many days do you spend in the building in a normal working week? *Days per week in building*

How many hours per day do you spend in the building on a normal working day? *Hours per day in building*

How many hours per day do you spend at your desk or normal work area on a normal working day? *Hours per day at desk*

How many hours per day do you normally spend working with a computer screen (VDU)? *Hours per day at VDU*

The building overall

Building design — All things considered, how do you rate the building design overall? *Please select* Unsatisfactory [1] [2] [3] [4] [5] [6] [7] Satisfactory — *Comments about design overall*

Needs — In the building as a whole, do the facilities meet your needs? *Please select* Unsatisfactory [1] [2] [3] [4] [5] [6] [7] Satisfactory — *Comments about needs overall*

Space — In the building as a whole, do you think that space is used ...? *Please select* Ineffectively overall [1] [2] [3] [4] [5] [6] [7] Effectively overall

Image — How do you rate the image that the building as a whole presents to visitors...? *Please select* Poor [1] [2] [3] [4] [5] [6] [7] Good

Safety — How do you rate your personal safety in and around the building ...? *Please select* Poor [1] [2] [3] [4] [5] [6] [7] Good

Cleaning — How do you rate the cleaning ...? *Please select* Unsatisfactory [1] [2] [3] [4] [5] [6] [7] Satisfactory

Availability of meeting rooms *Please select* Unsatisfactory [1] [2] [3] [4] [5] [6] [7] Satisfactory — *Comments about meeting rooms*

Suitability of storage arrangements *Please select* Unsatisfactory [1] [2] [3] [4] [5] [6] [7] Satisfactory — *Comments about storage*

Your work — Please briefly describe the work that you carry out in this building ...? *Work description*

Your work requirements

Specifically, for the work that you carry out, how well do the facilities meet your needs ...? *Please select* Very poorly [1] [2] [3] [4] [5] [6] [7] Very well

Please give examples of things which can hinder effective working ...? *Hinder*

... and examples of things which usually work well ...? *Work well*

Your desk or work area

Furniture — How do you rate the usability of the furniture provided at your desk or normal work area ...? *Please select* Very poor [1] [2] [3] [4] [5] [6] [7] Very good

Space at desk — Do you have enough space at your desk or normal work area ...? *Please select* Too little [1] [2] [3] [4] [5] [6] [7] Too much

Comments about your desk or work area

Under licence from BUS Methodology Copyright © 2015 Page 1 of 3

Figure 2. Sample section from the BUS survey, including scalable responses and comment boxes.

An online questionnaire was used to record longitudinal feedback from occupants. The questionnaire contains six questions on perceived environment (thermal sensation and preference votes, air quality, noise, lighting, overall comfort) and one question on change in perceived productivity due to the environmental conditions. The commonly used seven-point Bedford scale[1] for thermal comfort was used to record perceived thermal comfort, and rating scales (1-7; 1: unsatisfactory and 7: satisfactory) identical to those used in the BUS survey were used for air quality, noise, lighting and overall comfort. Occupants were also asked to rate their change in perceived productivity on a scale from -20% or more to +20% or more with 5% increments. The questionnaires were sent via email three times a day (morning, midday and afternoon) during three weeks from April-July 2017.

Simulated performance tasks were conducted in two rounds (of approximately two working weeks) during the non-heating season, to provide an assessment of task performance alongside the monitoring of indoor environmental conditions occurring at the time. Three different sets of performance tasks were selected from those used in previous research studies (Wargocki et al, 2000, 2002, Park and Yoon, 2011). The tasks were designed to represent typical office tasks and consisted of: *Numerical tests* (to solve simple mathematical questions), *Proof reading* (to identify spelling errors in a paragraph of text) and *Stroop test* (an interference test, differentiating between the colour of the text and the word). Both the *test score* and *time taken* to complete the task were recorded. Tasks were designed to take no more than 10 minutes each to complete, so as to increase participation and minimise disruption to daily work. They were sent via email twice-daily (morning and afternoon) from 7th-13th June 2017 and 24th-28th July 2017. This provided performance data for the non-heating season. Since the project began in February, it was not possible to conduct online survey and performance tasks in the heating season because of the time taken to establish access to, and engagement with, the building's occupants.

Repeating surveys and tasks (multiple times per day and over at least a one-week period) ensured that a range of indoor environment conditions were recorded which is typical of naturally ventilated buildings, and also reduces potential bias in participation.

3.1. Overview of the case study

The case study building is located in central London next to a busy road. It was built in 1938 and fully refurbished in 1995. It is primarily an owner-occupied office building. Heating and cooling is provided by fan coil units. The seventh floor of the case study building was selected as the case study working environment for this project. The floor is home to an open-plan administrative department (approximately 400m^2 with 78 workstations). Desks, carpets and other furnishing in all areas of this floor were upgraded (replaced) in 2015. Lights were controlled locally and the official operating hours during the working days (i.e. hours the space was controlled for heating and cooling) were from 08:30 to 17:30. The study space was divided into four monitoring zones as shown in Figure 3. The average daily occupancy from February to July is 48 (occupancy rate of 61.5%). (Note: occupancy data were available from February to the first half of July).

[1] Bedford Scale: 1 – Much too cool 2 – Too cool 3 – Comfortably cool 4 – Comfortable neither warm nor cool 5 – Comfortably warm 6 – Too warm 7 – Much too warm

Characteristics of case study working environment

Region: London
Location: Urban
Type of facility: Open-plan office
Ownership: Owner occupied
Date of construction: 1938
Date of refurbishment: 1995
Predominant construction type: Brick/stone and block insulated cavity
Heating: Fan-coil units beneath outdoor windows
Ventilation/cooling strategy: Natural ventilation and fan-coil units beneath outdoor windows

Figure 3. External view of building (top left), indoor view of zones A3 and A4 (top right), floorplan showing zones (bottom left) and descriptive characteristics of the case study working environment (bottom right).

4. Data analysis

4.1. Indoor environment (heating and non-heating periods)

A comparison of the distribution of indoor temperature during working-hours in both heating (February-April) and non-heating (May-July) seasons is shown in Figure 4. This shows significant overlap, but lower averages and a smaller range in the heating season.

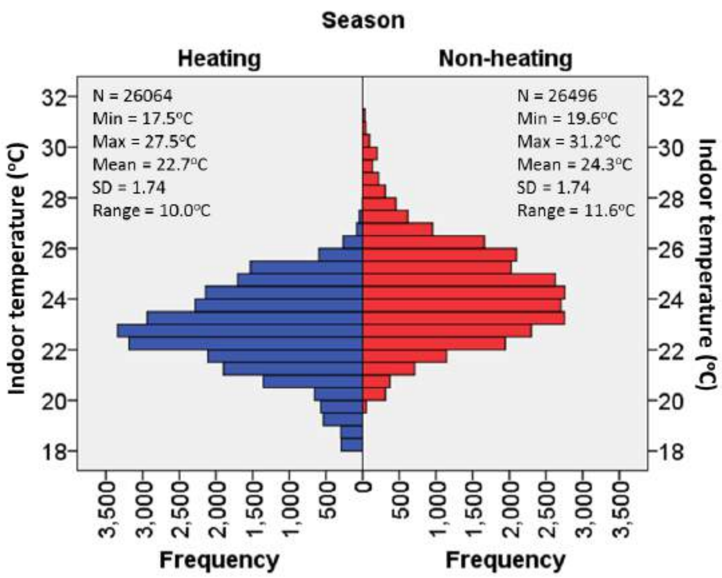


Figure 4. Comparison of working-hours indoor temperature distributions in the heating and non-heating seasons.

To gain a deeper understanding of the relationship between indoor and outdoor temperatures across the heating and non-heating seasons, Figure 5 shows scatter plots with linear trendlines and 95% confidence intervals plotted. The dashed line shows where indoor and outdoor temperatures were equal. In the heating season, temperatures were found to be higher internally than externally for more than 97% of the time. This dropped to 85% in the non-heating season. The link between outdoor and indoor temperatures is stronger in the non-heating season (Pearson correlation r=0.10 and r=0.53 in the heating and non-heating seasons respectively), when windows were more likely to be opened. There is also a narrower range of temperatures in the heating season compared to the non-heating season.

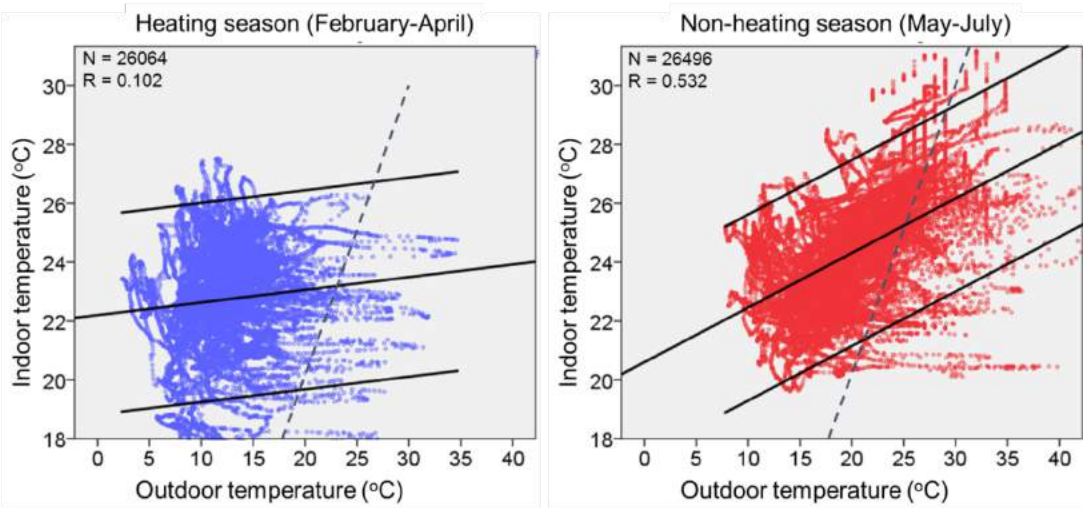


Figure 5. Relationship between outdoor and indoor temperatures in heating season (left) and non-heating season (right), showing linear trendlines and 95% confidence intervals. Dashed line shows when indoor and outdoor temps were equal.

Boxplots of indoor temperatures for each month in Figure 6 indicate the median, upper and lower quartiles for readings taken at 5-minute intervals. Mean outdoor temperatures and occupancy are also shown. Peak outdoor temperatures in June correspond with longer upper whiskers on the boxplot and more outliers above this. Taking February as a sample month for the heating period, and July as a sample month for the non-heating period, mean indoor temperatures in July were approximately 1.5°C higher compared to February.

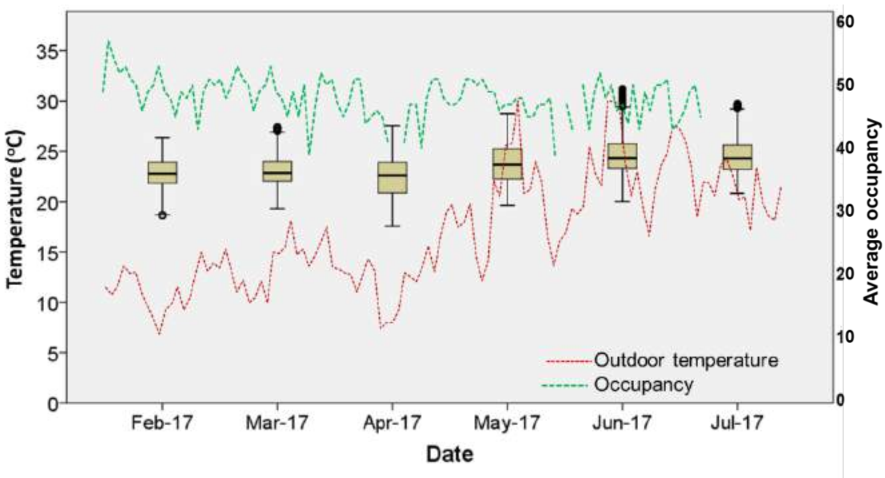


Figure 6. Distribution of temperatures each month, showing median and interquartile range, outdoor temperature and occupancy.

Investigating further into hourly temperature profiles for February and July, Figure 7 shows mean hourly temperatures averaged overall all four zones. During occupied hours, indoor temperature is found to increase by an average of 2.7°C in February and 1.7°C in July.

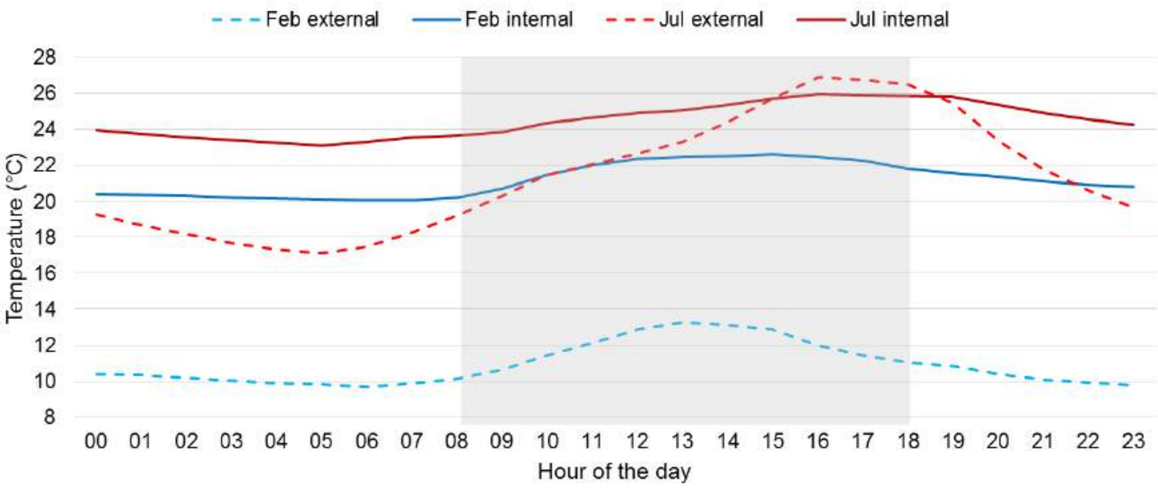


Figure 7. Hourly temperature profiles in February and July.

Recommended temperatures for thermal comfort in UK in offices is 21-23°C in the heating season and 22-24°C in the non-heating season (CIBSE, 2015). In both February and July, indoor temperatures in the case study working environment were within the recommended ranges for less than 15% of the occupied hours, and exceeded these ranges for over 80% of occupied hours. Analysis of thermal sensation and preference votes later in the paper will help to corroborate this.

Average indoor humidity (Figure 8) is found to be at the lower limits of the recommended 40-70% range (between 40-50% for over half of the occupied hours) in the heating season as the space was continuously heated.

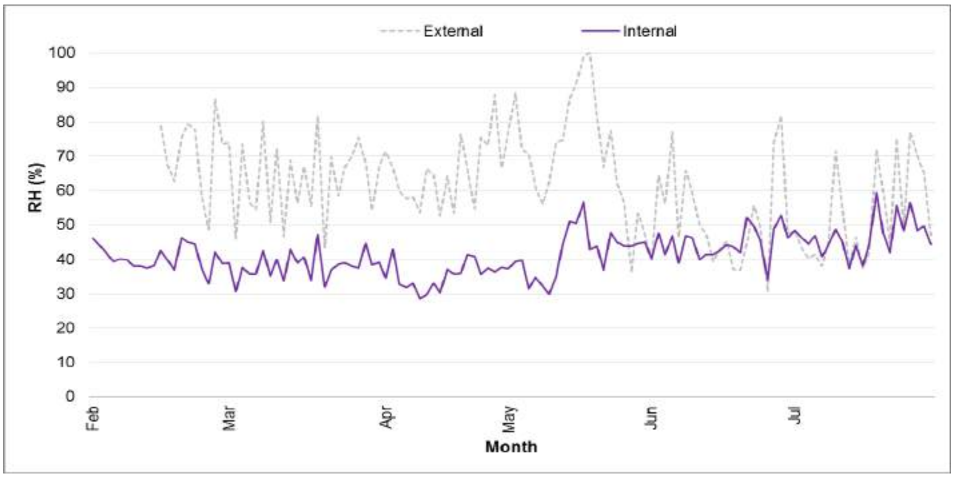
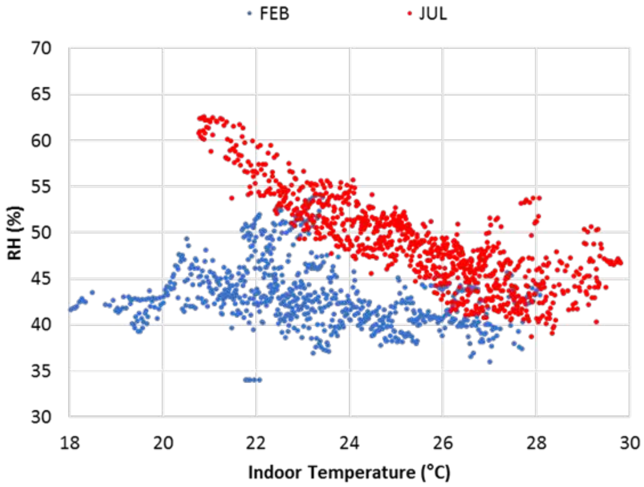


Figure 8. Daily average outdoor and indoor relative humidity (RH).

This is further confirmed when indoor RH is plotted with concurrent measurements of indoor temperature (Figure 9). Drier conditions (lower RH values) were observed in February compared to July, even at the same temperature. In July, relative humidity was within the recommended range (40-70%) for most of the occupied hours possibly due to no space heating and windows opening.



Descriptive statistics

	Feb (N=790)		Jul (N=893)	
	Temp. (°C)	RH (%)	Temp. (°C)	RH (%)
Min	18.0	33.9	20.8	38.7
Max	28.1	54.1	29.8	62.5
Mean	23.2	43.1	25.4	48.9
SD	2.22	3.48	2.15	4.91

Figure 9. Scatter plots and descriptive statistics of indoor temperature and RH during working hours in February and July.

The distribution of indoor CO_2 levels for the six months is shown in Figure 10. Maximum daily CO_2 concentrations exceed 2500ppm in February and April (when windows were found to be closed), while In July, maximum daily CO_2 concentrations were around 1500ppm. In all months, the distribution of CO_2 levels is positively skewed. Interestingly the interquartile range (difference between lower and upper quartiles) of CO_2 concentrations is much larger in the heating months (especially February) compared to the non-heating months, indicating wider fluctuations in CO_2 concentrations over the course of a day. This is confirmed by the daily profiles of CO_2 concentrations wherein the profile in February shows a much greater variation over the course of a day (Figure 11). For both months, as expected, CO_2 levels start to increase from around 08:00 and decrease from 17:00, coinciding with when members of staff arrive at the start of the work day and when they leave at the end. Furthermore, in February CO_2 concentrations above 1500ppm occurred for almost 30% of the occupied hours, predominantly during the afternoons, while in July, occurrences of concentrations above 1500ppm were much lower – less than 1% of occupied hours. Open windows in the summer were likely to be the main cause of these significantly lower levels.

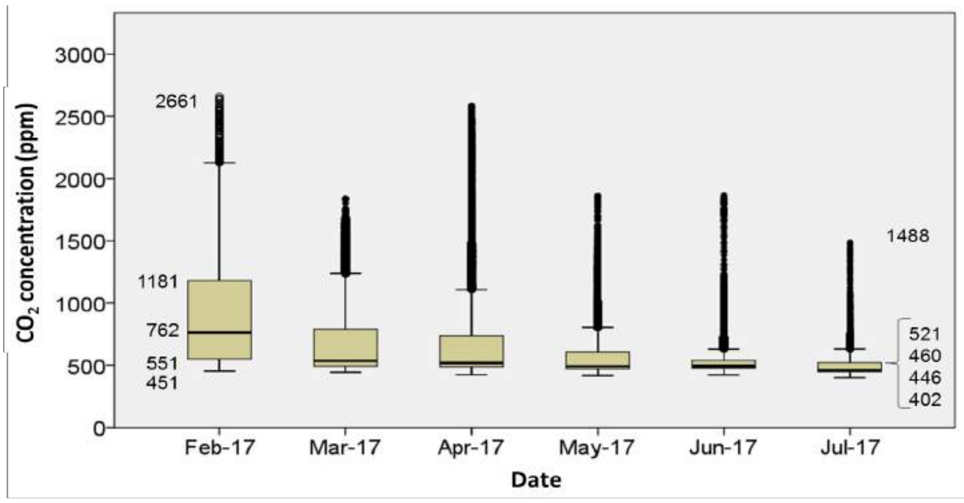


Figure 10. Distribution of CO_2 levels showing max/upper quartile/median/lower quartile/min for February and July.

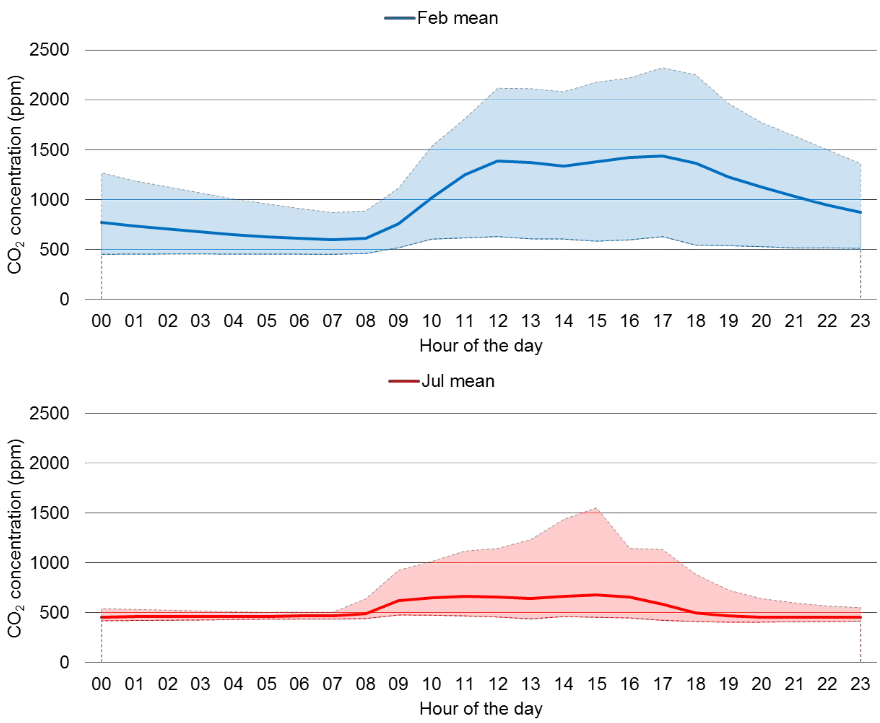


Figure 11. Hourly CO_2 profiles in February (top) and July (bottom), showing average maximum and minimum for each hour.

The wide range in CO_2 levels is again evident throughout February when the daily minimum/mean/maximum CO_2 concentrations were plotted alongside daily occupancy (Figure 12). In February, there is some suggestion that CO_2 levels may be related to occupancy with, for example, drops in both aspects around 10^{th} and 20^{th} February, and a rise in both from 24^{th}-28^{th} February. In July the link between occupancy and CO_2 concentration is less evident – the added factor of window openings is likely to negate any effect of occupancy levels.

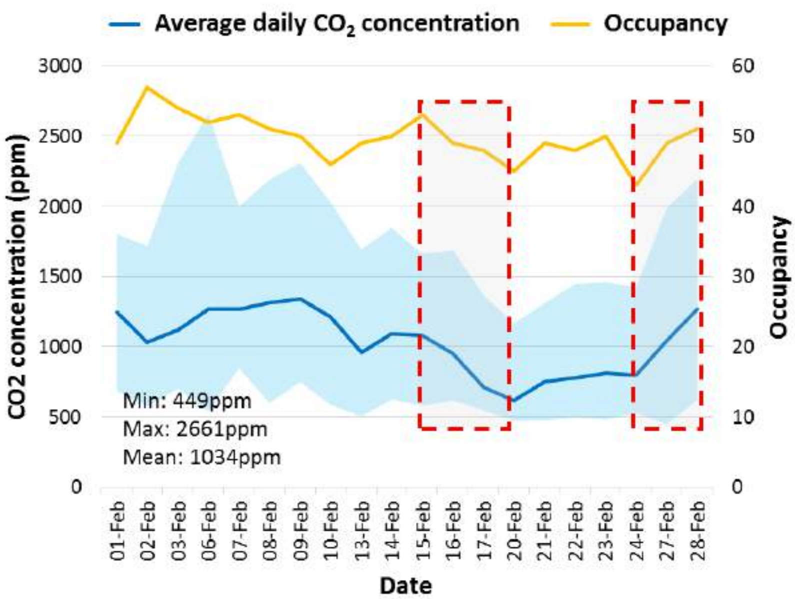


Figure 12. Daily indoor CO_2 profiles (min, mean, max) and daily occupancy in February 2017, with interesting periods highlighted.

4.2. Transverse survey of occupant perception of indoor environment and productivity

The BUS occupant survey was conducted as transverse survey on 28 March 2017. Questionnaires were handed out to occupants between 10:00 and 11:00. Completed questionnaires were collected between 16:00 and 16:30 on the same day. About 62 questionnaires were completed from 78 workspaces, representing a 79% response rate. Analysis of the responses showed a balance between gender and age groups. Over 50% of the respondents have been working in their work area for at least one year, implying they have experienced both heating and non-heating seasons in the building. Table 3 presents the mean average scores (scale of 1-7) of key environmental variables and change in perceived productivity. Scores were highlighted *red* (1.0-3.4), *amber* (3.5-4.5) and *green* (4.6-7.0). Responses regarding the building (design, space, cleanliness etc.) were broadly positive, all averaging a score of 4.8 or above.

Table 3. Average scores from respondents from the BUS survey (scale of 1-7)

Study variables	**Average response**
Temperature and air quality conditions in winter	
Temperature: Uncomfortable/Comfortable	**4.5**
Temperature: Too hot/Too cold	**4.5**
Air quality: Still/Draughty	**3.2**
Air quality: Dry/Humid	**3.3**
Conditions overall	**4.4**
Temperature and air quality conditions in summer	
Temperature: Uncomfortable/Comfortable	**3.2**
Temperature: Too hot/Too cold	**2.6**
Air quality: Still/Draughty	**2.9**
Air quality: Dry/Humid	**4.2**
Conditions overall	**3.4**
Noise conditions	
Unsatisfactory/Satisfactory	**4.4**
Lighting conditions	
Unsatisfactory/Satisfactory	**4.8**
Personal control	
Heating: No control/Full control	**1.2**
Cooling: No control/Full control	**1.2**
Ventilation: No control/Full control	**1.1**
Satisfaction with response to request change	**3.2**
Comfort and health	
Overall comfort: Unsatisfactory/Satisfactory	**4.7**
Change in productivity (perceived)	
Decreased/Increased	**-5.8%**

It is realised that occupants were generally satisfied with their working environment (especially noise and lighting conditions), although there was less satisfaction with the thermal and air quality conditions. For both summer and winter, occupants reported that temperature varied during the day and the air was still and stuffy. Occupants found the air dry (average score 3.2) in the winter, and more humid (average score 4.6) in the summer, as also confirmed by the measured humidity levels recorded in the case study space (Figure 9). The lowest scores given were for personal control of the environment: occupants reported that they have very little control over heating and cooling, and they were not satisfied with the speed of response to requests to change the environmental conditions. Interestingly, overall comfort in the building was rated as satisfactory, yet perceived productivity was found to decrease by 5.8% due to the environmental conditions.

Variables associated with the perceived environment were correlated with a change in perceived productivity to assess their relationship. Correlation coefficients are presented to indicate the direction and the strength of the relationship (Table 4). Spearman's rho test (a non-parametric test), is used here because the relationships being tested were not linearly related. A negative, albeit weak, correlation was found between indoor temperature variation and productivity (more varied temperatures correspond to a perceived reduction in productivity). A positive, but weak, correlation was found between air movement and perceived change in productivity (less air movement corresponding to a perceived reduction in productivity). Moderate correlations were also found for overall comfort, indicating that when occupants were more comfortable (due to the environmental conditions in the building), their perceived change in productivity is positive. This is further substantiated by the longitudinal survey responses and performance tasks discussed in the following sections. Since these were conducted in May, June and July, the cross-relation with physical monitoring data is during the non-heating (summer) period.

Table 4. Spearman's Rho correlation coefficients between perceived indoor environment and change in productivity.

Study variables	**Correlation (N=58)**
Perceived temperature and indoor air quality conditions in winter	
Temperature: Stable/Varies during the day	-0.34*
Air quality: Still/Draughty	0.24
Comfort and health	
Overall comfort: Unsatisfactory/Satisfactory	0.49*

*Correlation is significant at the 0.01 level (2-tailed)

4.3. Longitudinal survey of perceived productivity and comfort and measurement of indoor environment

Two rounds of online surveys were conducted in April-May 2017 (two weeks) and July 2017 (one week) to gather data on occupant perception of thermal comfort, indoor environment and productivity. A link to the questionnaire was sent via email to the occupants. The response rate dropped from 69% in Round 1 to 39% in Round 2. Since the surveys were time-stamped, the responses could be related to the concurrent measurement of the indoor environment.

The distribution of thermal sensation votes correlated with indoor temperatures in show in the figure below, with the trendline and 95% confidence intervals. As indoor temperature increases, thermal sensation votes move towards the warm end of the scale.

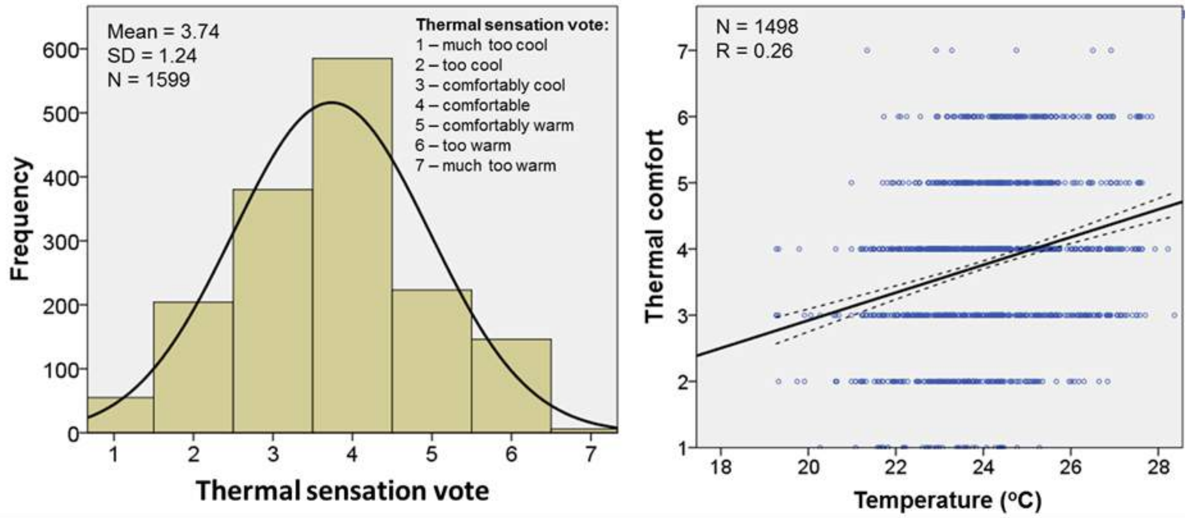


Figure 13. Thermal comfort vote distribution (left) and scatter of comfort vote and indoor temperature with linear regression line and error lines (right).

Figure 14 shows the distribution of air quality votes and correlation with CO_2 concentrations, with the trendline and 95% confidence intervals. Air quality votes were skewed towards the stuffy end of the spectrum, and the trendline indicates that occupants perceive the air quality as stuffier as CO_2 concentration increases. Interestingly the correlation coefficient is weaker (r= 0.11) than that of thermal sensation and indoor temperature (r= 0.26).

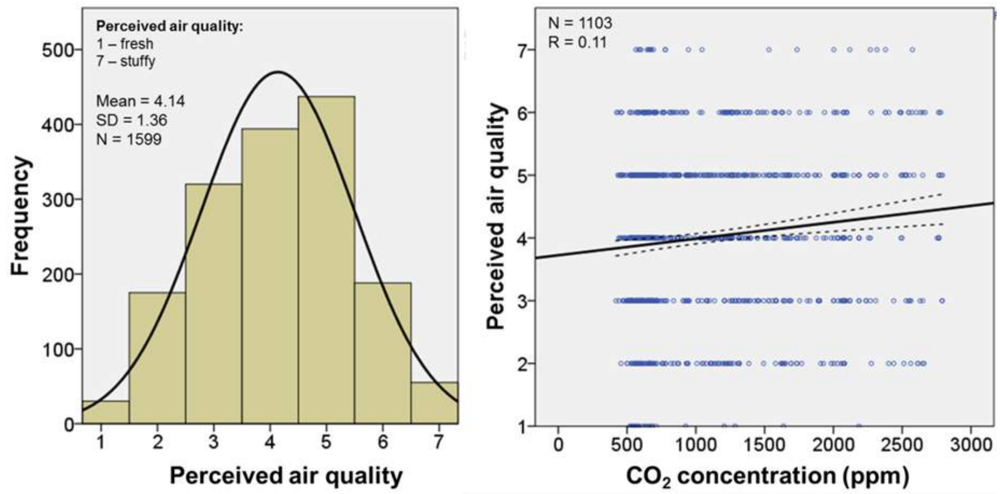


Figure 14. Air quality vote distribution (left) and scatter of air quality vote and CO_2 concentration with linear regression line and error lines (right).

Furthermore the measurements of indoor temperature and CO_2 concentrations were analysed when perceived change in productivity was negative, neutral (no change) and positive (Figure 15) during the three weeks of the longitudinal survey (April, May and July). The distribution of indoor temperatures changes slightly depending on the perceived change in productivity: the mean temperature is slightly higher (24.17^{o}C) when productivity is perceived to be reduced and slightly lower (23.97^{o}C) when productivity is perceived to be increased compared to the neutral 'no perceived change in productivity' (24.10^{o}C). For CO_2 concentration, there is a slight shift towards lower levels of CO_2 when change in productivity is perceived to be positive, although there is only a 5% difference in mean CO_2 concentrations between the negatively and positively perceived changes in productivity.

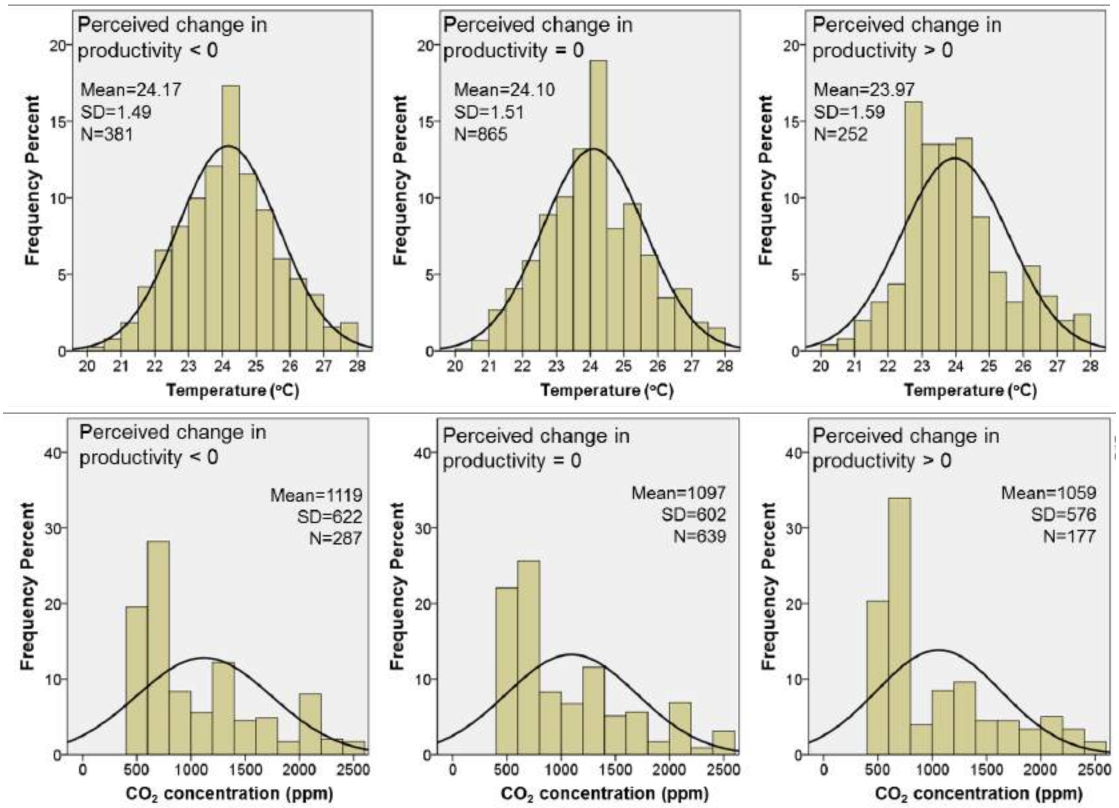


Figure 15. Distribution of indoor temperature (top) and CO_2 concentration (bottom), when change in perceived productivity was negative, neutral and positive during the three weeks in April, May and July 2017.

Overall thermal comfort vote and perceived change in productivity decreased during the course of the day (Figure 16) over the survey period of three weeks. While the occupants perceived their productivity to increase at the start of the day (+0.2%), by late afternoon, this had decreased to -1.6%.

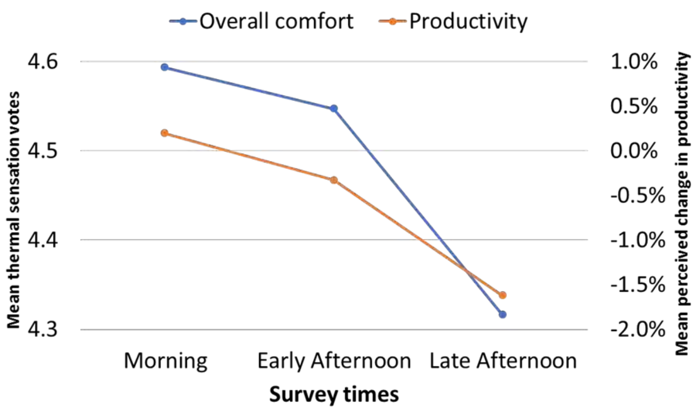


Figure 16. Average thermal comfort votes and perceived change in productivity.

Interestingly when cross-relations were investigated during the course of a day (Figure 17), changes in the thermal sensation and air quality votes strongly relate to changes in measured indoor temperatures and CO2 levels. While the thermal sensation vote changes from being comfortably cool to comfortably warm during the course of the day as indoor temperature rises, indoor air quality which is perceived to be fresh in the morning moves towards the stuffy end of the scale in the late afternoon, as indoor CO2 levels increase.

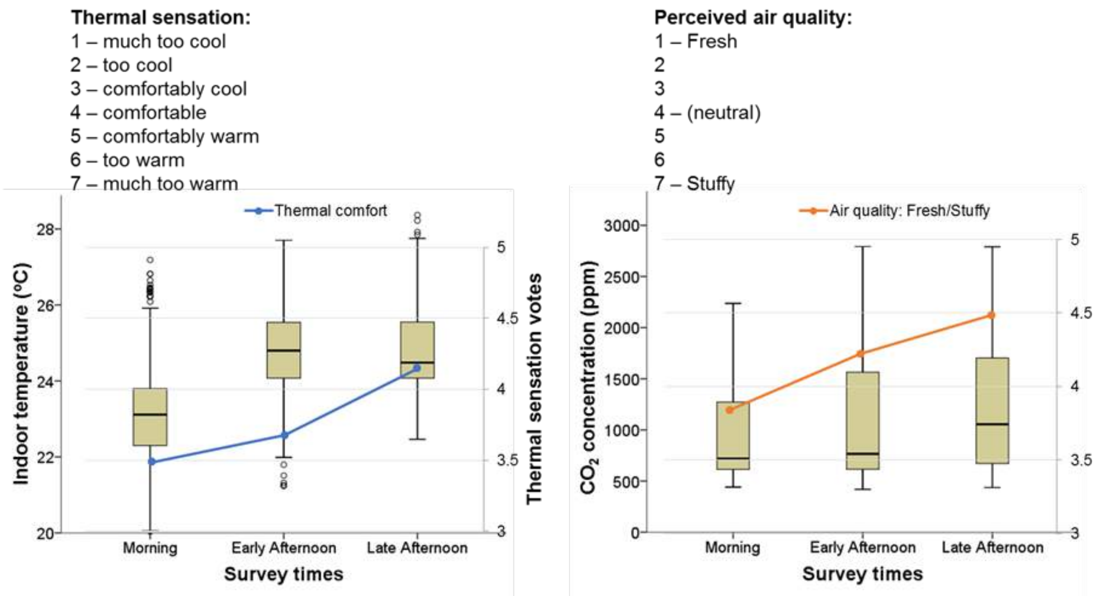


Figure 17. Change in daily mean thermal sensation vote and indoor temperature (left) and perceived air quality and CO_2 levels (right) in the non-heating period.

This was further reconfirmed in the mean thermal preference votes. Despite over half of the respondents not wanting a change in their thermal environment (Figure 18), there was a notable shift from morning to afternoon amongst respondents who wanted to be a bit warmer in the morning to a bit cooler in the afternoon. This could, in part, be explained by the influence of the working environment's west-facing orientation, which receives more direct solar gains in the afternoon.

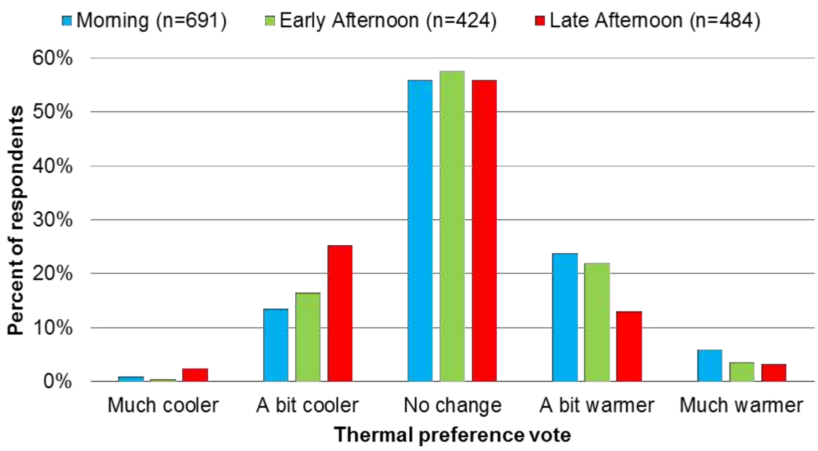


Figure 18. Thermal preference vote throughout the day.

4.4. Measuring productivity and indoor environment

Two rounds of performance tasks were conducted (lasting two working weeks) during the non-heating season to objectively measure the performance of staff. As with the online surveys, the performance tasks were time stamped and the indoor environment conditions at the time of completion were recorded. The response rate dropped from 39% in Round 1 to 32% in Round 2. Three different sets of performance tasks were selected which included - *Numerical tests* (to solve simple mathematical questions), *Proof reading* (to identify spelling errors in a paragraph of text) and *Stroop test* (an interference test, differentiating between the colour of the text and the word). The highest scores were recorded in the Stroop test, with participants scoring an average of 98%, while the lowest scores were recorded in the proof reading test. Interestingly in all three tests, there was little difference between the proportion of correct answers recorded in the morning and in the afternoon.

Figure 19 presents scatter plot of the proportion of correct answers in the proof-reading tasks compared to measured indoor CO_2 levels. It is realised that there is a negative but weak correlation between these two sets of data implying that lower scores correspond to higher levels of CO_2. Correlations between scores of other tests and indoor environmental parameters (temperature and RH) were even weaker, indicating that the indoor environment had little role to play in influencing the score of the performance tasks.

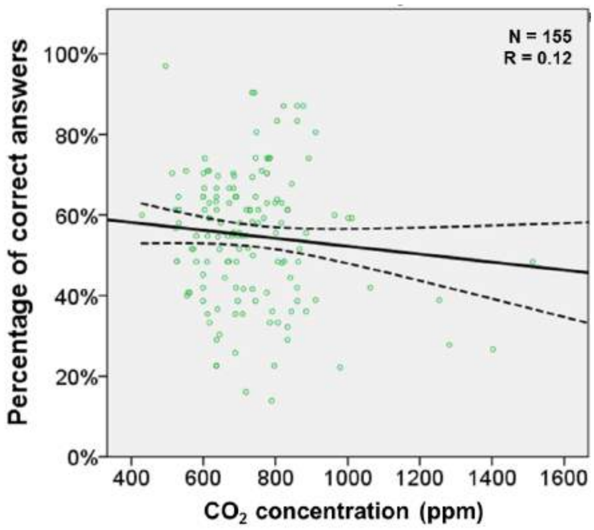


Figure 19. Scatter plot showing the relationship between proportion of correct answers in the proof-reading test and corresponding CO_2 concentration, with 95% confidence interval (dashed line).

Performance was also assessed in terms of time taken to complete the tasks. It took participants an average of 8.8, 9.0 and 2.4 minutes to complete the numeric test, the proof reading task, and the Stroop test respectively. The trendline in Figure 20 indicates that higher temperatures tend to lead to tests taking longer to complete, although again, correlations were very weak. It is worth noting that the times taken to complete the tests was measured from a start and end time rounded to the nearest minute, which, for such short time scales, gives a low degree of granularity in the data.

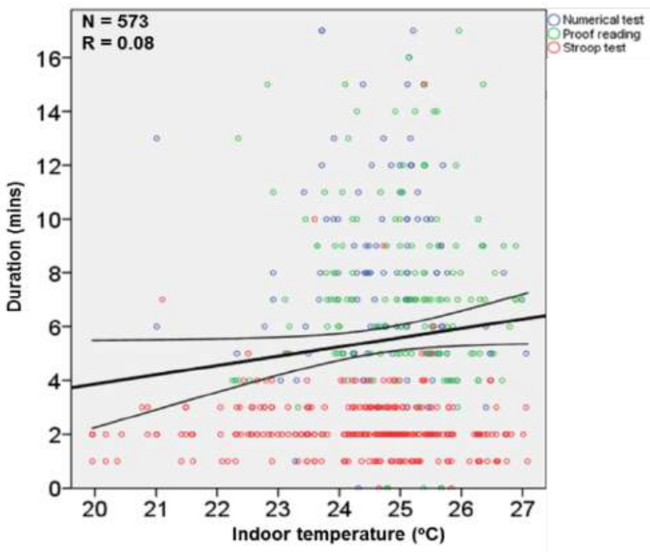


Figure 20. Scatter plot showing relationship between time taken to complete tasks and indoor temperature.

5. Discussion

In line with field studies of thermal comfort, mean indoor temperatures were found to strongly correlate with mean outdoor temperatures more in the non-heating season (May-July) than in the heating season (February-April). Although indoor temperatures have a wider range in the non-heating season (from 20^{o}C to over 30^{o}C) compared to the heating season (18-26^{o}C), during the course of a typical working day, the increase in indoor temperature in the heating season is higher compared to the non-heating season (2.7^{o}C compared to 1.7^{o}C respectively). This is likely to be due to opening of windows in the non-heating season which helps in reducing diurnal temperature fluctuations. However there were constraints related to having window opening as a means of heat management (such as outdoor air pollution and outdoor noise), given the central London location of the case study.

Indoor RH is found to be lower in the heating season (typically in the mid-40's) when the heating serves to dry the air and the closed windows prevent outdoor humid air (typically around 80% in the heating season) entering the building. Conversely, CO_2 levels were higher in the heating season (higher peaks, higher diurnal ranges, higher averages) compared to the non-heating seasons. Reluctance to open windows in the heating season to vent CO_2 allows indoor CO_2 levels to increase throughout the working day.

The results from traverse and longitudinal surveys concur. The BUS survey indicated a negative correlation between temperature variability and perceived change in productivity, and a positive correlation between perceived overall comfort and perceived change in productivity. These findings were supported by the results of the longitudinal (online) surveys, which also identified a positive correlation between thermal comfort and perceived change in productivity. The online surveys found weak but significant correlations between indoor temperature and productivity (perceived increase in productivity corresponding to a lower mean temperature), and between indoor CO_2 concentration and productivity (perceived increase in productivity corresponding to a lower mean CO_2 concentration). Neutral responses for thermal sensation vote (comfortably cool/comfortable/ comfortably warm) covered a wide range of temperatures. This indicates there is no set temperature that is going to please everybody, which implies the role of adaptation. Likewise, a positive change in perceived productivity was recorded at a wide range of temperatures and CO_2 levels.

Interestingly, weak correlations were found between the outputs from the performance tasks and indoor environment. However, there was a negative (but weak) correlation found between proof-reading scores and CO_2 concentration (higher levels of CO_2 corresponding to lower scores) and a positive (weak) correlation found between proof-reading durations and indoor temperatures (higher temperatures corresponding to longer times taken to complete the tasks).

It is evident from the study that collecting empirical data of sufficient quality and quantity can be difficult when partnering with case study organisations. Data loggers can be set up and left to collect indoor environment data continuously with minimal interference to staff. However, measuring productivity is beset with challenges. Business output metrics, such as number of calls made or e-mails sent, proved to be very difficult to get access to despite being relevant to a study which has the potential to increase staff productivity. Likewise HR data, such as occupancy rates and absenteeism, were unavailable due to data protection and privacy issues. Self-reported productivity required occupants to take time to respond to surveys, while measured productivity required occupants to take even more time to respond to tasks. For empirical studies such as this, occupant engagement should be an integral part of research design, in order to ensure good response rates.

Establishing and maintaining good working relationships with the management and staff members is paramount. When staff members become disengaged or lose interest, response rates drop and the potential for disingenuous responses increases. Regular communication with participants, including some general feedback on their responses to date, can help keep their interest in the study although it requires resourcing in terms of time and manpower. Incentives for participants may help to improve response rates, but could also encourage 'straight-liners' and 'speeders' (those who respond with the same answer each time or too quickly to have given the questions any thought), leading to bad data. In short, secondary datasets (business output metrics and HR data) proved extremely difficult to access; primary datasets (surveys and tasks) proved difficult to gather.

It is also realised that optimising indoor environment to improve productivity is inherently more challenging than finding ways to worsen it. For instance, increasing indoor CO_2 levels above 2000ppm or setting indoor temperatures below 19^{o}C or above 28^{o}C, would likely lead to a decrease in productivity given the findings from longitudinal surveys, whereas finding the optimum threshold for indoor CO_2 or temperature to maximise productivity is much more challenging.

6. Conclusions

The study has provided interesting results through continuous physical monitoring and surveys of a case study working environment in central London, during the heating and non-heating periods. Despite the interesting findings, the study faced a number of challenges that are implicit in studies conducted in 'real world' settings (as opposed to studies conducted under tightly-controlled laboratory conditions). Isolating factors that can positively or negatively affect productivity is challenging. In reality, a wide range of factors, both scalable (such as indoor environment) and nominal (such as what someone had for breakfast or lunch) may influence productivity. Determining how much each factor plays a role in increasing or decreasing productivity is therefore challenging.

There are also ethical and data-protection issues that arise with collecting HR data such as occupancy and absenteeism. Data on business output metrics (used as proxy for productivity) were found difficult to obtain, even when anonymised. An organisation may, for many reasons, be reluctant to release these business output data to an external party.

Nevertheless, despite these challenges, this study has found empirical evidence that suggests indoor environment is related to workplace productivity. Therefore by managing the indoor environment effectively, there is potential to improve productivity, which is the next step in the WLP+ research project.

7. Acknowledgements

The authors would like to thank EPSRC (Grant ref: EP/N509000/1) and Innovate UK (Application number: 54815-413475) for funding the WLP+ research project under the *Building Whole-Life Performance* competition. The authors are grateful to LCMB (lead industry partner) and KINGS College (project partner) for their exceptional efforts with occupant engagement. The authors are also thankful to Jonida Murataj and Dr Adorkor Bruce-Konuah for their assistance in data collection.

8. References

Alker, J. et al., 2014. Health, Wellbeing & Productivity in Offices: The next chapter for green building. World Green Building Council. Available at: http://www.worldgbc.org/sites/default/files/compressed_WorldGBC_Health_Wellbeing__Productivity_Full_Report_Dbl_Med_Res_Feb_2015.pdf (Accessed: 10th Dec. 2017).

Allen, J.G. et al., 2015. Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. Environmental Health Perspectives, 124(6), pp 805-812. [Accessed: 13th Dec. 2017].

Al Horr, Y. et al., 2016. Occupant productivity and office indoor environment quality: A review of the literature. Building and Environment, 105, pp 369-389.

British Council for Offices, 2017. Defining and measuring productivity in offices. [online] Available at: http://www.bco.org.uk/Research/Publications/Definingandmeasuringproductivityinoffices.aspx [Accessed: 13th Dec 2017].

Browning, B., 2016. Biophilia, Buildings, and Your Brain. People and Strategy, 39 (2), pp 8-11.

BUS Methodology, 2018. BUS Methodology. [online] Available at: http://www.busmethodology.org.uk [Accessed: 9th Jan 2018].

CEN, 2007. Standard EN15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Bruxelles: European committee for Standardisation.

CIBSE, 2015. Environmental design, CIBSE guide A. London: CIBSE.

Coggon, D et al., 2013. Disabling musculoskeletal pain in working populations: Is it the job, the person, or the culture? Pain, 154(6), 856–863.

Fang, L. et al., 2004. Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance. Indoor Air, 14(7), pp 74–81.

Gupta, R. et al., 2016. Desktop investigation to examine the relationship between indoor environmental conditions and productivity in work spaces. SEEDS Proceedings 2016, pp 189-201

Kajtar, L. et al., 2003. Examination of influence of CO2 concentration by scientific methods in laboratory. In Healthy Buildings. Singapore.

Kajtár, L. et al., 2003. Examination of influence of CO2 concentration by scientific methods in the laboratory. Proceedings of Healthy Buildings, 2003(3), pp 176-181.

Lan, L. et al., 2011. Effects of thermal discomfort in an office on perceived air quality, SBS symptoms, physiological responses, and human performance. Indoor Air, 21(5), pp 376–390.

Niemelä, R. et al., 2002. The effect of air temperature on labour productivity in call centres—a case study. Energy and Buildings, 34(8), pp 759–764.

ONS, 2014. Long term sickness absence. [online] Available at: https://www.gov.uk/government/statistics/long-term-sickness-absence [Accessed 17th May 2016].

Park, J.S. & Yoon, C.H., 2011. The effects of outdoor air supply rate on work performance during 8-h work period. Indoor Air, 21(4), pp 284–290.

Satish, U. et al., 2012. Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance. Environmental Health Perspectives, 120(12), pp 1671–1677.

Seppänen, O. et al., 2006. Effect of Temperature on Task Performance in Office Environment. Lawrence Berkeley National Laboratory. [online] Available at: https://indoor.lbl.gov/sites/all/files/lbnl-60946.pdf [Accessed: 13th Dec. 2017].

Shahzad, S. et al., 2016. Building-Related Symptoms, Energy, and Thermal Control in the Workplace: Personal and Open Plan Offices. Sustainability, 8(4), p 331.

Smith, L. et al., 2016. A review of occupational physical activity and sedentary behaviour correlates. Occupational Medicine, 66(3), pp 185–192.

Tham, K.W., 2004. Effects of temperature and outdoor air supply rate on the performance of call center operators in the tropics. Indoor Air, Supplement, 14(7), pp 119–125.

Vimalanathan, K. & Babu, T.R., 2014. The effect of indoor office environment on the work performance, health and well-being of office workers. Journal of Environmental Health Science & Engineering, 12, pp 1–8.

Wargocki, P. et al., 2002. Subjective perceptions, symptom intensity and performance: a comparison of two independent studies, both changing similarly the pollution load in an office. Indoor air, 12(2), pp 74–80.

Wargocki, P. et al., 2000. The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. Indoor air, 10(4), pp 222–236.

Witterseh, T. et al., 2004. The effects of moderate heat stress and open-plan office noise distraction on office work. Indoor air, 14(8), pp 30–40.

Thermal comfort and air quality: one-year measurement, analysis and feed back to users of an educational building

Sébastien Thomas, Samuel Hennaut and Philippe André

University of Liège, BE, Arlon Campus Environment, 185 Avenue de Longwy, 6700 Arlon, corresponding author sebastien.thomas@uliege.be;

Abstract: Whereas thermal comfort and air quality in buildings are often measured locally and over a short-term period, the complaints of user may occur everywhere in the building regardless the time of the day or the season. The dynamic nature of indoor environments make it hard to closely assess and compare the comfort conditions in the day-to-day life within all the spaces of a building over time. In this study, thermal comfort and air quality have been measured in four teaching rooms in a university building located in Belgium. The analysis gives a letter (A-B-C or D) for the comfort and the air quality for each room. The computed level of thermal comfort and air-quality is shown to users on a yearly and monthly basis via the TV screen located in the building. The vulgarisation, or sharing of the results with the building occupants makes the users aware of their own impact on comfort conditions and the options available for them to improve them through their own actions. The whole year gathered data illustrates the various occupancy patterns and highlights the opportunities to improve comfort:. On the one hand, the results shown a low air quality, the CO_2 thresholds have been modified. On the other hand, the summer comfort, was found to be poor in two rooms. This argues with the landlord to do something to improve the comfort especially in these rooms.

Keywords: CO_2 measurement, thermal comfort, air quality, feedback to users

1. Introduction

Buildings are expected to allow people to live, work and entertain themselves under optimum conditions of comfort. Most people spend more than 80% of their time indoors, if not more. Therefore many are concerned about comfort in buildings. This reveals multiple aspects such as hygrothermal comfort, visual comfort, acoustic comfort and air quality. All comforts are highly subjective and often lead to complaints from tenants. It is consequently crucial to objectivize the feelings of people. In the context of university buildings, a better comfort increases the value of learning and boost wellbeing of both students and teachers.

In this work it is proposed to assess the thermal comfort and air quality of several teaching spaces. Long term measurements are run, they enable to give feedback to users and to improve the comfort conditions.

2. Building description

The building monitored is a 1985-building located in the Arlon campus of University of Liège (south of Belgium). The small town, nearly rural, host the campus in a 3-hectare green park.

The 840m² net floor area building includes auditoriums, seminar rooms, and offices (named B1 to B5 on figure 2). For the purpose of this work, only rooms used for teaching are considered (4 rooms). It is a concrete building with 12 cm mineral wool insulation. The two auditoriums are half underground; this ensures a better summer thermal comfort for those areas. Another particularity of the building is the large glazed area on south façade (figure 1). External-solar protections are not working anymore. There is a buffer space behind the south façade as viewed on figure 2. On a HVAC point of view, the building is heated by a gas burner and radiators, air handling units provide fresh air to the rooms, dampers allow selecting the destination of mass flow. There is no recirculation, no heat recovery, a heating coil and a single speed fan. All those equipment are 30-year old, the control has nevertheless been updated. Automatic control are implemented, the user has the only opportunity to turn the thermostatic valve of the radiators.

In this study, the thermal comfort and air quality have been measured in four teaching rooms (respectively 10, 20, 50 and 100-people rooms) listed in table 1. Two of them are displayed on figure 1.

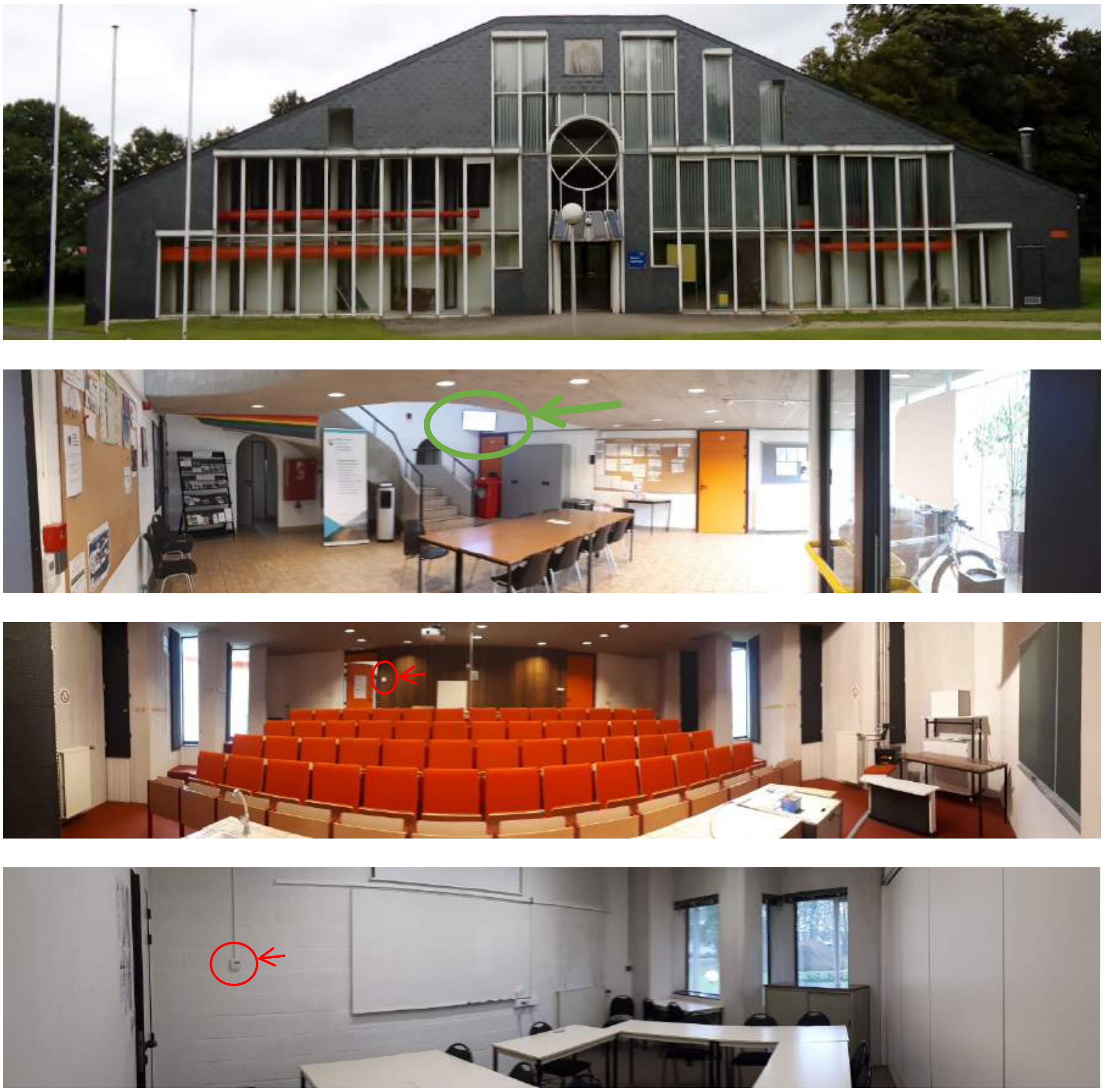


Figure 1. Picture of the Academic Building, from top to bottom: outside view of South façade, ground floor hall, auditorium 2, seminar 2.

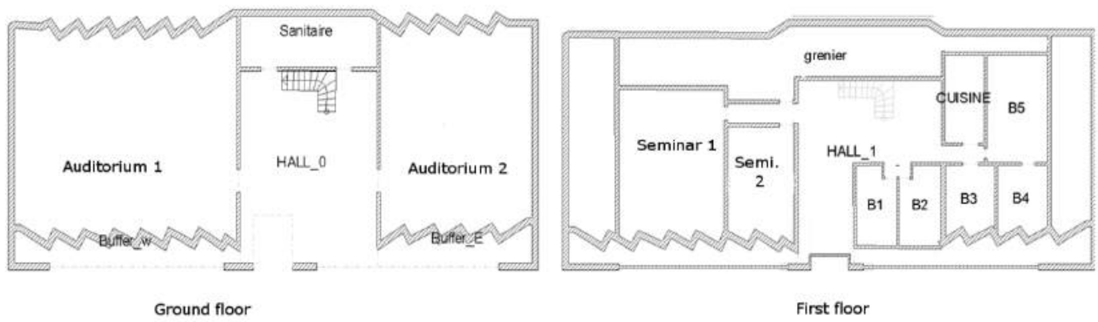


Figure 2. Schematic view of the building (Lakrafli,2008)

Table 1. Listing of monitored rooms

	Size [m²]	Max. attendance [pers.]	Sensors
Seminar room 1	52	24	Air t°, RH , CO2
Seminar room 2	25	12	Air t°, RH , CO2
Auditorium 1	171	120	Air t°, RH , CO2
Auditorium 2	112	50	Air t°, RH , CO2
Whole building	840	/	Outdoor t°, wattmeter

3. Monitoring description

A building monitoring system is fit to the building, it consist of plenty of sensors and actuators controlling heating devices, ventilation, doors, outside lighting. The booking of rooms is also connected to the monitoring system. This implies knowledge of the occupancy of the various rooms. For this study, the air temperature, relative humidity and CO_2 concentration are recorded with one integrated sensor (see technical data in table 2) using a sampling period of 5 minutes. There is permanently one sensor per monitored room, it is shown in a red circle on figure 1. All the collected data is stored on a server we consult each month for the data analysis.

3.1. Thermal comfort

The ISO 7730:2005 standard is used to evaluate the thermal comfort. The categories are described in table 2. As for the PPD computation more parameters are required, some assumptions must be drawn. We assume the following lines are a strong hypothesis, which was a compromise to have continuous PPD evaluation throughout the year.

Table 2. categories of thermal environment and air quality (International Organization for Standardization ,2005) (Bureau of Standardisation NBN, 2007) Outside CO_2 level is set to 410 ppm

Category	PPD from ISO7730 table A.1	Air quality NBN EN13779 Table A.10
A	<6	Measured CO_2 < 810 ppm
B	<10	Measured CO_2 < 1010 ppm
C	<15	Measured CO_2 < 1410 ppm
D	>=15	Measured CO_2 >= 1410 ppm

- Air temperature: measured ($T_{air\ in}$)
- Relative humidity: measured
- Clothing: 0.5-1 (the teachers and students are able to choose their clothing – the lowest PPD value is taken into account)
- Activity: 1.2 met (sedentary activity school)
- Surface temperature: worst case taken into account, computed using the measured outside and inside air temperatures as well wall U-value.
- Air speed: set to 0.1 m/s. Some punctual measurements were achieved, there was no high speed recorded.

The outside air temperature ($T_{air\ out}$) is measured in the building neighbourhood without any radiation effect. Inside surface temperature is computed as follows (without any dynamic effect):

$$T_{surf} = T_{air\ in} - U_{wall}\frac{T_{air\ in} - T_{air\ out}}{h_{in}}$$

Where U_{wall} = 0.298 W/(m²K) (using 10 cm concrete and 11 cm mineral wool)
h_{in} = 7.7 W/(m²K) (representing the heat transfer from internal surface to air).

Let's give a few details about the air speed hypothesis. The air speed is very complicated to measure in a permanent way for each sitting place in each room. Some measurement undertaken in a short period of time did no raise any high air speed. No air draught is encountered due to lack of opening windows in the rooms and adequate sizing of the ventilation system. This is clearly an advantage for winter comfort, but a real issue in summer. This is not possible to cool the building with fresh air from windows. For summer comfort the same hypothesis is taken into account (low air speed).

Table 3. Sensor EE80-2CSD04 technical description (Airtesttechnologies.com 2017)

	Technology	Range	Accuracy
CO_2	Non Dispersive IR	0-2000 PPM	@ 20°C ± (50 ppm +2 % of measuring value)
T°	CTN	-5 to 55°C	@ 20°C ± 0.7°C
RH	Capacitive	10-90%	@30-70% ± 3%

3.2. Indoor air quality

The EN13779:2007 standard is used to evaluate the air quality. The categories are also described in table 2. The assumption of base outside CO_2 level of 410 ppm has been taken into account. This has clearly no impact on results as the CO_2 sensor is auto-calibrated to lowest value of 410 ppm within a period of one week. The viewpoint of the standard EN13779 is the gap between inside and outside CO_2 concentration.

3.3. Occupancy

As mentioned below, the booking of rooms is also connected to the monitoring system. The room can be separately booked (15 minutes sample), the comfort and air quality are only computed when the room booking flag is on.

3.4. Electrical consumption

Despite not detailed in this work, the electrical consumption has been recorded and compared to standard DIN V 18599:2007. This standard gives target but no categories. The Luxembourgish legislation besides uses this standard and specify categories (Ministry of Economy, Luxembourg, 2010). The building electricity consumption has been compared to the Luxembourgish legislation. The result are quite good due to the efficient lighting, CO_2 based ventilation and low number of appliances. Those measurements are no more detailed in this work.

4. Data analysis

The measurements detailed in §3 were run throughout year 2016, they were analysed each month to give feedback to users (§5). July is not mentioned as there is no one in analysed rooms (university holidays). A deeper analysis has been done in the beginning of 2017 with all the data collected previous year.

4.1. Global results

These are mainly shown on figure 7 for yearly results, this set of diagrams is purposed to feedback users and inform the landlord and staff to make decisions about the works to undertake.

The **thermal comfort** category for each room are gathered and displayed for each month. The y axis represents the occupancy percentage. Relative period of time has been chosen for presentation and comparison purpose.

For the seminar rooms, a “D” category (meaning a significant lack of comfort) is pointed out in table 4. There is a great lack in thermal comfort especially in the 1st floor in extreme season.

Those measurements led to increase the ventilation temperature set points and to renew the motor of a roof-top fan evacuating building heat in summer.

Table 4. Worst month where “D” category was found in the seminar rooms for thermal comfort

Under heating	**Month**	**Occupancy [%]**	**Duration [h]**
Seminar room 1	November	18	30
Seminar room 2	January	20	34
Over heating			
Seminar room 1	August	23	20
Seminar room 2	August	16	14

For the auditorium, better comfort conditions have been encountered (semi buried rooms with large inertia increase summer comfort). Only January in Auditorium 1 encountered significant D letter 11% of the time. The ventilation set point increase seemed to solve the problem. For both type of rooms, sometimes the user turns the thermostatic valve, so the thermal comfort conditions are not met anymore for the following hours … to the following day. In other words, the user disturbs the thermal comfort. Moreover, to explain bad comfortable conditions, the occupancy period taken into account is based on room reservation, which is not always consistent as explained in §4.2.

The analysis regarding the percentages does not reveal the hour of uncomfortable conditions. Generally the occupancy taken into account is between 150 and 200h per month. August is partly holiday; the occupancy of each room is 88h.

The **air quality** based on CO_2 measurement revealed a suitable ventilation operation for all the rooms. The CO_2 based ventilation permits good air quality (class A or B) all over the year. In seminar 2, 100% of occupancy has encountered a class A or B. In seminar 1, only one hour period with class C has been encountered. For the auditorium, sometimes when both auditoriums gather a significant number of people, the class C is encountered. It appeared less than 1% of the total recorded period. The summary graph does not show much data about air quality.

4.2. Focus on specific days.

First, **a typical day** result is displayed on figure 3. It shows the typical operation of the building and the kind of measurement we recorded most of the time (i.e. low PPD and CO_2 levels). Computed PPD is displayed with markers for each room in order to explain thermal comfort. The markers are set to zero when there is no room reservation. The CO_2 levels describe the air quality and occupancy of each room. Outside temperature is displayed in all graphs of this paragraph to appreciate the weather conditions.

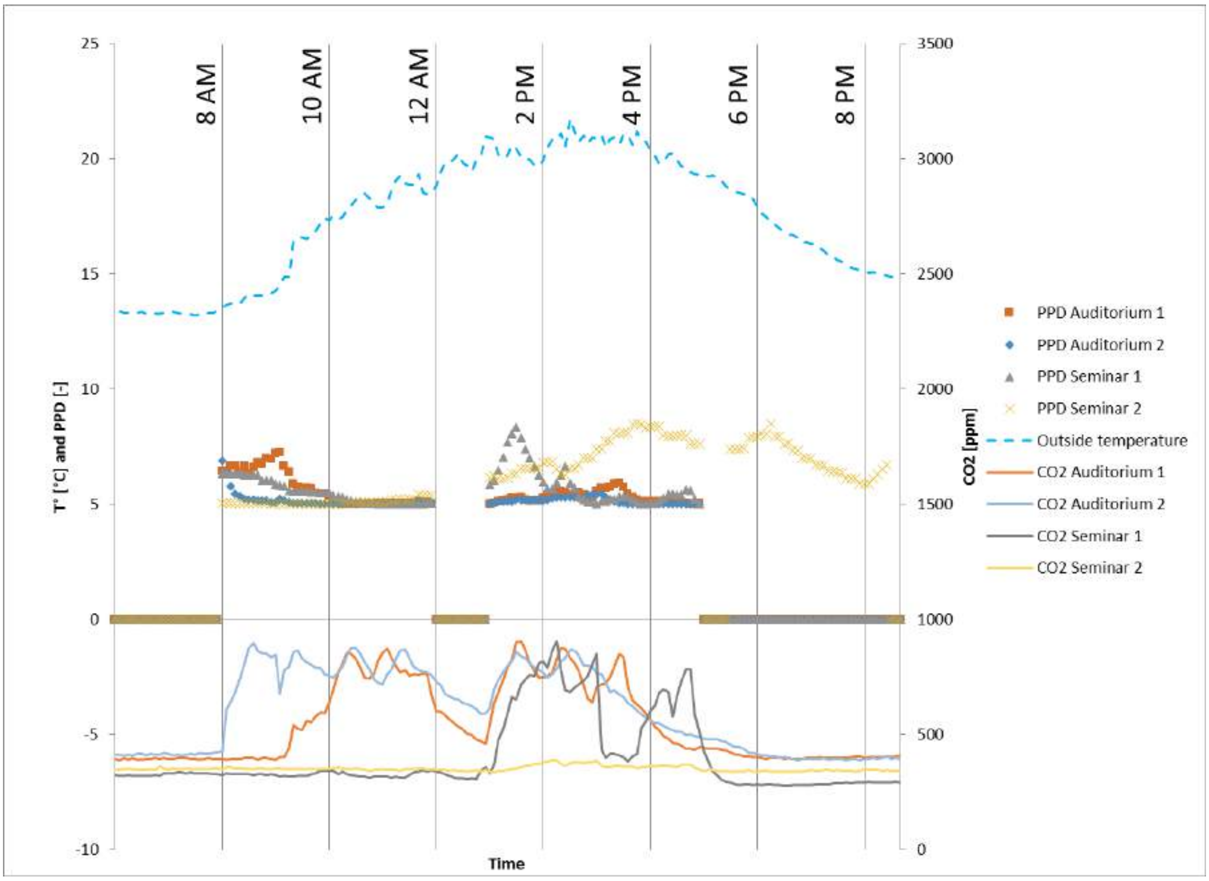


Figure 3. Typical day results (29th September 2016) : CO_2 level, PPD computation and outside t°

Figure 3 gives the typical reservation pattern: for weekdays, all rooms are booked from 8 to 12 AM, from 1 to 5 PM, and some rooms (e.g. seminar 2) are booked for evening classes or over events. Despite the reservation, the lessons take place or not, with a delay or on time! The CO_2 level increasing over 500 ppm defines a presence of people in the room. In auditorium 1, the lesson started at about 9 AM, auditorium 2 it started at 8 AM. In seminar 1, the lesson was only given in the afternoon and there were no lessons this day in seminar 2. This emphasizes the lack of confidence in reservation data (it will also be the case for the next specific cold and hot days). About thermal comfort, the PPD value is generally lower than 10%, it could be a little bit higher at the beginning of the day when the building has not warmed up enough.

The CO_2 level reach peaks at around 900 ppm CO_2. This is the threshold for starting the ventilation. The CO_2 level sail through 400 and 900 +/- the tolerance of the sensor (table 2). The sensor are auto-calibrated to 410 ppm on a weekly basis.

A **cold day** (5^{th} January) is displayed on figure 4 to illustrate the lack of comfort recorded in winter. The occupancy patterns show a low comfort especially when there is no one in the room (low CO_2 concentration). The two seminar rooms have sometimes too low comfort; the wrong position of the radiator thermostatic valve and lack of ventilation boost (i.e. 21°C set-point at that time) can explain this. As seen for seminar 1 in the afternoon, the comfort conditions become better directly after occupancy start. For seminar 2 in the afternoon, the CO_2 level suggests a low occupancy, and a considerable lack of comfort for those few people (between classes C and D). The discrepancy between reservation and actual occupation is also highlighted on figure 4. The auditorium 1 has still high CO_2 level in the afternoon despite there is no one in the room, so the occupancy could not be directly linked with the CO_2 level (but with its evolution over time).

This cold day is representative of the experienced lack of thermal comfort in winter days due to two main reasons:

- Ventilation set-point too low
- Probability of user modification of radiator thermostatic valve

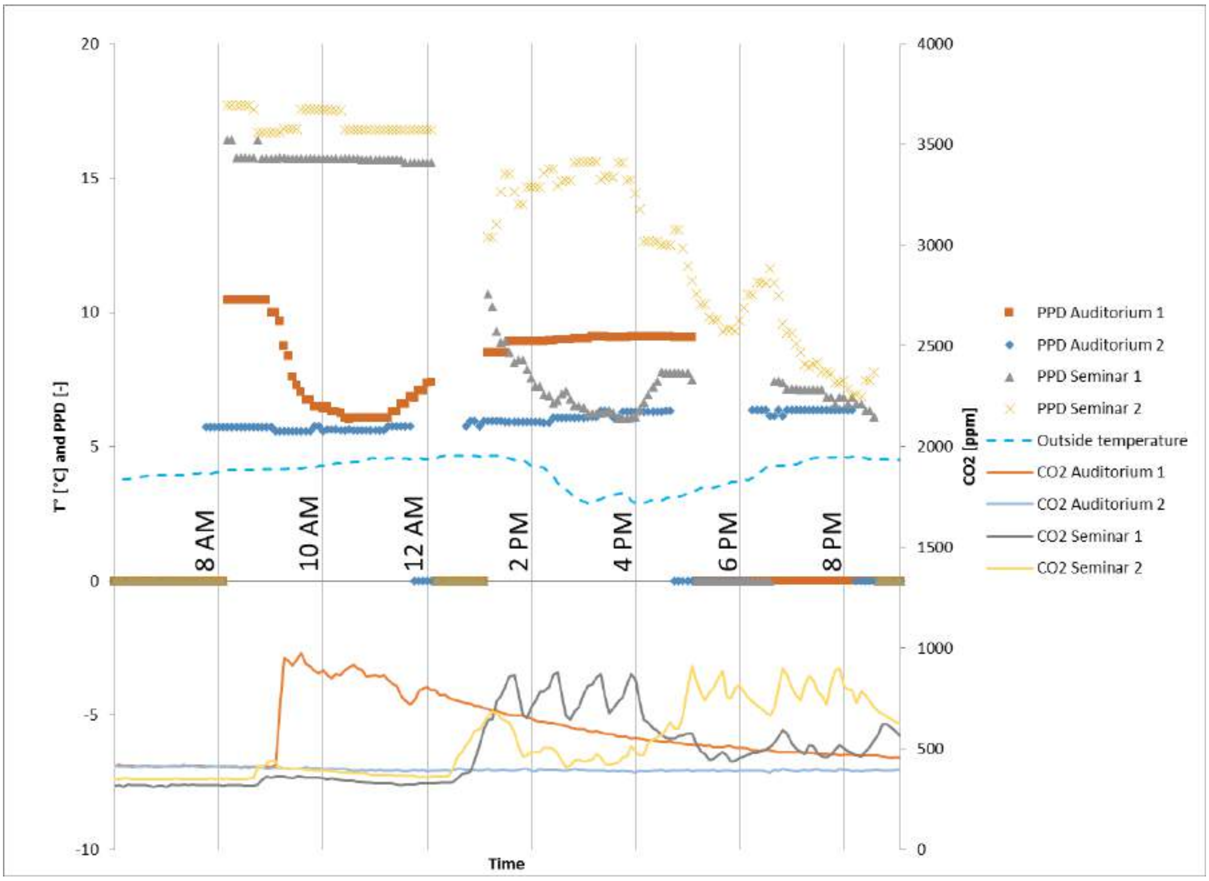


Figure 4. Cold day results (5^{th} January 2016) : CO_2 level, PPD computation and outside t°

A **hot period** (13th September) is displayed on figure 5, it depicts what happens in the seminar rooms in case of hot weather. Some stuff differ from the two previous graphs:

- The auditorium 1 is not mentioned as it was not used this day.
- The measured air temperature in each room is displayed to emphasize the overheating.
- Only the end of the day is displayed as there was no daily lesson this day (only evening classes between 6:30 PM to 8:30 PM)

The 1st floor includes the seminar rooms and as no active cooling. During the day the solar gains enter the building and heat spreads through wall and internal windows to the seminar rooms. Those are not ventilated, the temperature stays at a high level. This implies a very high PPD at the beginning of the occupancy period (around 50% for seminar 2). The large inertia maintains a high temperature (30°C in seminar 2) despite the ventilation with lower outside air at around 22°C. Seminar 1 and 2 encounter generally high air temperature in summer, the only heat sink is the ventilation. For security reasons the doors are locked when no occupancy; the natural ventilation is therefore not influencing the temperature in those rooms.

The auditoriums meet good thermal comfort conditions whatever the outside temperature (not only for this day but for the whole hot season see fig.3). In case of long heat wave, a natural ventilation is possible through an emergency exit on the bottom of each of the auditoriums, those allows crossing natural ventilation.

This hot day is representative of the experienced lack of thermal comfort in seminar rooms in hot summer days. This is due to two main reasons:

- Lack of shading devices
- No ventilation (heat sink) when no people inside the rooms

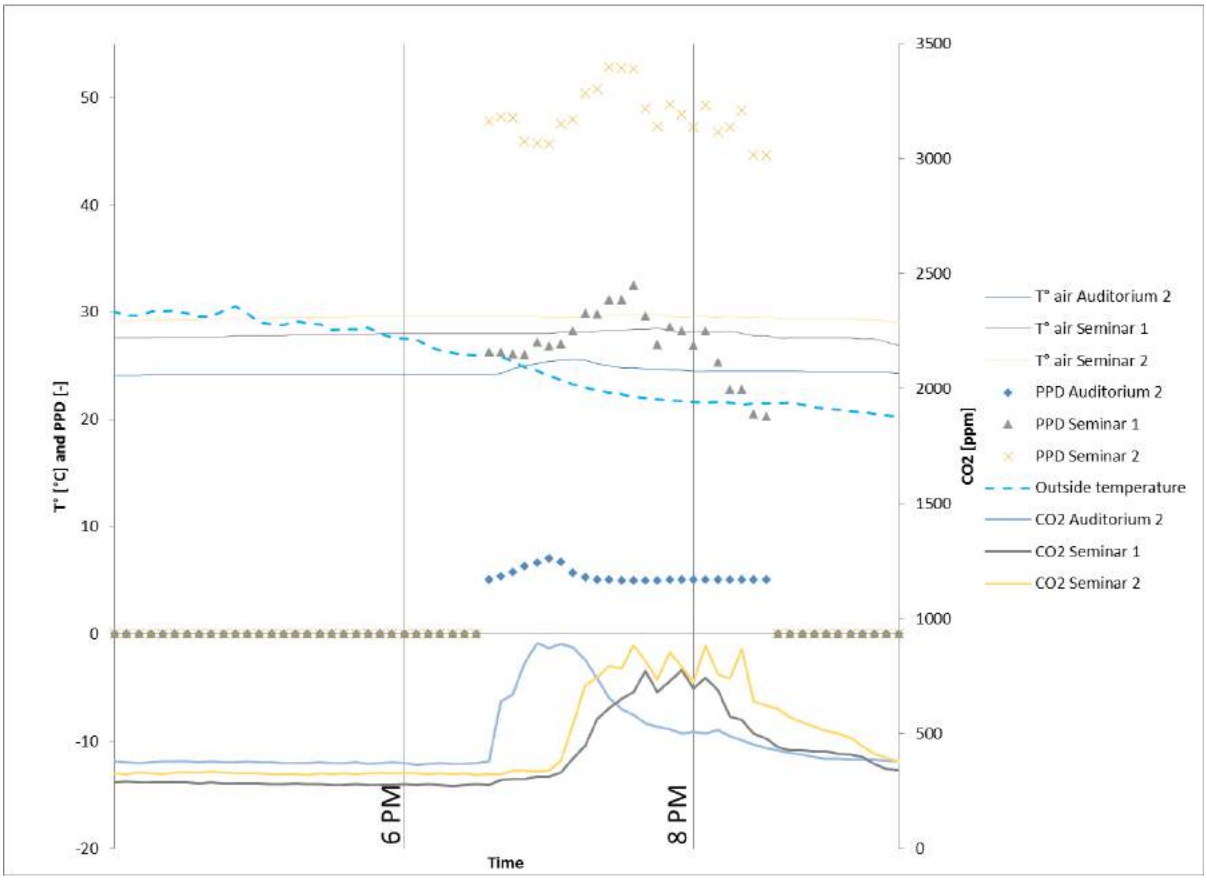


Figure 5. Hot day results (13th September 2016) : CO_2 level, PPD computation, inside and outside t°

4.3. Limitations

- With the diagram of figures 6-7 (using only letters A-D), it is not possible to check if there is a problem of under heating or over heating while analysing yearly results. The letter only specifies a gap between the current conditions and optimal conditions; care should be taken to verify the data to be sure a “D” does not mean an overheating in winter!
- Only one probe is placed in the area, this limits a lot the comfort analysis and forces us to make a set of assumptions. As a first improvement, a second probe could be placed in auditorium to catch the temperature gradient in the room.
- Occupancy is based on booking of rooms, sometimes the rooms are booked and there is no one inside as illustrated before (§4.2). This clearly affects the results: On the one hand, the air quality is better (no CO_2 production) and of the other hand the thermal comfort is worse (no one to turn the thermostatic valve, no internal gains). A better way to catch occupancy should be found: CO_2 level, lighting consumption, occupancy probe…)
- The CO_2 is the only indicator for air-quality in this study, additional measurements could be taken to attest the air quality (e.g. : VOC probes)
- Merging comfort conditions from different rooms over a long period request weights. We decided to give the same weight to each room; to be more consistent, a weighting should be done regarding the number of people present in the rooms.

4.4. Building improvements

Actions must especially be taken to improve summer comfort; a new motor for the exhaust fan on the top of the building has been installed since the measurement. It allows evacuating heat from hall and buffer space in summer. During summer 2016, the fan was not in operation. Moreover, the ventilation could be operated to cool the seminar rooms. As mentioned in §4.2, the seminar rooms are sometimes only used during the late afternoon and thus door closed during the day. The CO_2 based ventilation does not operate as there is no one inside. The operation of the ventilation should be driven by outside and inside temperature in those cases.

After the lack of comfort encountered in January 2016, the ventilation air temperature set point has been increased from 21 to 23°C. There was no more significant lack of winter comfort met in 2016. If required, a ventilation boost could be operated in winter in order to warm the room before occupancy. Likewise in summer the ventilation should be driven by inside temperature. Moreover, this ventilation boost competes against energy savings in the building.

At the end of 2015, the first measurements showed a lack of air quality. The CO_2 thresholds for starting and stopping ventilation were modified before year 2016 (cut-in is 850ppm instead of 1000ppm). This allowed reaching good air quality during the period analyzed in this work.

5. Feedback to users

User feedback is rarely described in studies, but becomes more and more important while improving comfort conditions and managing complaints in building (International Well Building Institute pbc and Delos Living, 2017). In this part of the work, the scope is to inform the users and the landlord to objectivize the possible complaints and to steer building/HVAC modifications.

A monthly result summary has been built (figure 6), the categories are clearly shown to ensure a quick and straight understanding of the reader. So, only one letter is set for the whole building for each criterion (each room is weighted by the occupancy duration). The letter shown is the worst category reached at least half of the occupancy period. More information about the percentage in each category is given on the right side to get the reader interested. Despite a good letter, a significant part of the period could be out of comfort conditions.

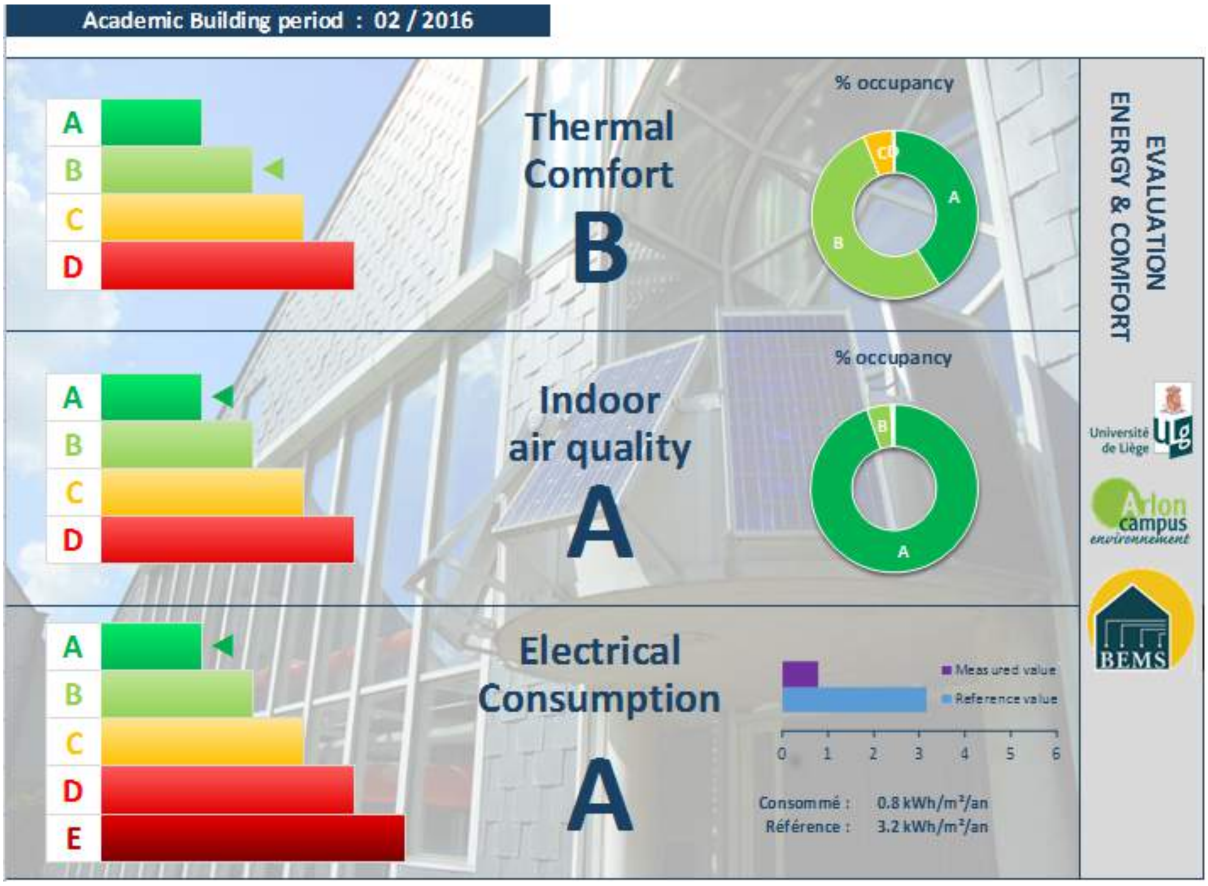


Figure 6. Monthly results

The yearly results summary (figure 7) is moreover dedicated to the landlord to take actions. In comparison with the monthly results, all the separated data from the four rooms are displayed. The quick understanding is not anymore pointed out. A more adequate diagram is set for each room and the letter selection hypothesis is highlighted. The diagram for each room tells the period with lack of comfort (e.g. August for seminar 1), a horizontal bar plot helps comparing the rooms. For electricity and air quality, there was no significant variation throughout the year, a single letter is appropriate to show the result. The letters highlighted are no more representing the half time occupancy (as for monthly results figure), but the 95% percentile which is much more restrictive. Thus, a 5% duration period outside of comfort is considered as acceptable (Bureau of Standardisation NBN, 2007), at least for overheating. A legend is added, it should have been also added for monthly results. The categories definition in the standards (table 2) is not easily comprehensible for non-technical staff, another description is given in the yearly results figure. Nevertheless it does not distort with the meaning of the standards ISO7730 and NBN EN13779.

From the user point of view, there are three ways to be informed about comfort:

- The sensor (red circle on figure 1) has a screen that allows the occupant to see the current measured temperature, humidity and CO_2 level.
- A web page has been set to explain the measurement to the building users (Thomas, 2016), a QR code was set to enable the occupants to easily access this page.
- A TV screen (green circle on figure 1) shows many pieces of information related to courses and events in the building. The results from the previous month are shown on this screen. The yearly results of 2016 were shown in early 2017.

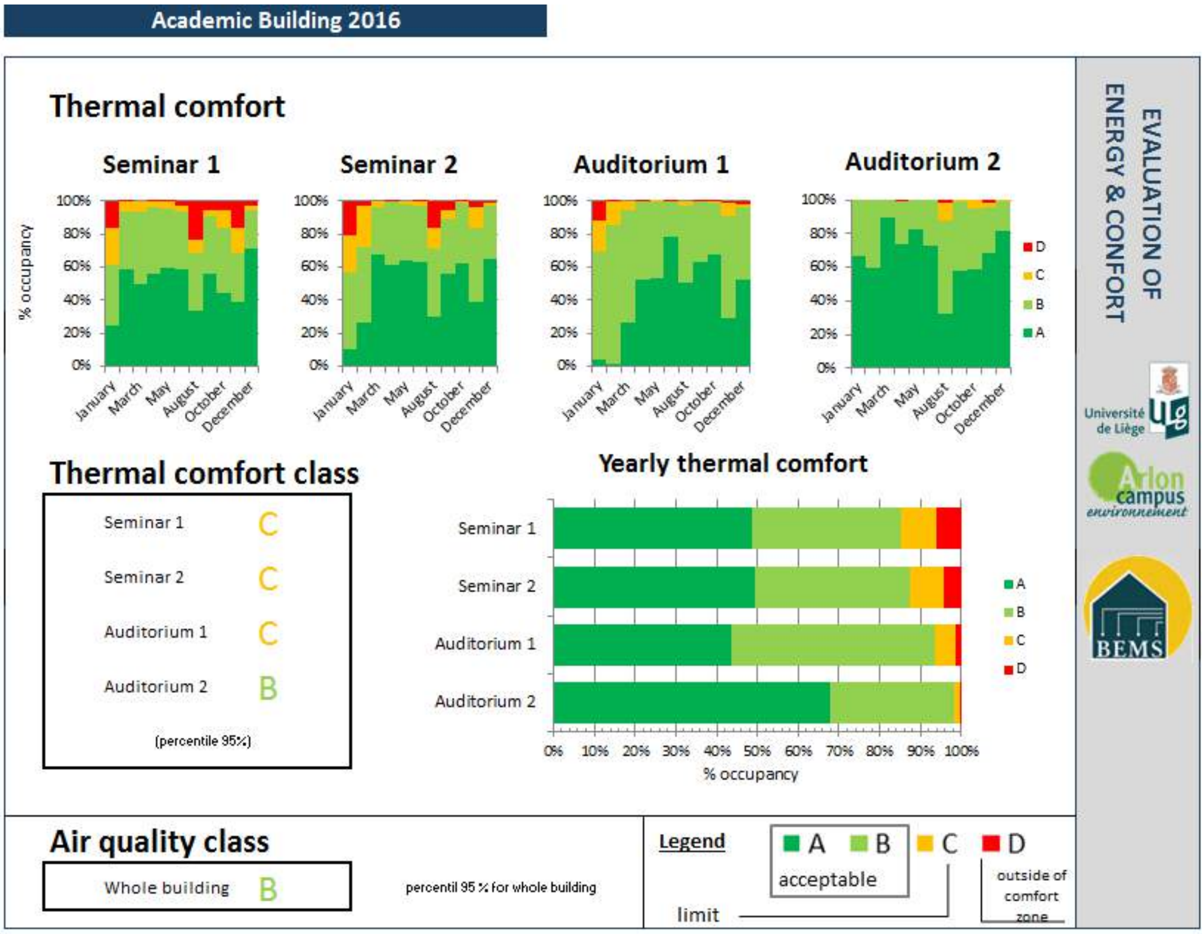


Figure 7. Yearly results

6. Conclusions and perspectives

This work concerns long term comfort measurement in an academic building. The **objectives** are to quantify what exactly were the comfort conditions experienced in it, to notify users of them and based on the findings of how that affected the actions of the users and resulting conditions achieved, provide a report for the landlord on where comfort problems exist over the year and how to improve them. To turn this study into a product capable of providing such a service in this and other buildings in the future a compromise has to be found between the reporting of the complexity of a complete academic comfort study and the measurement devices required to undertake it over the longer without disturbing the users and the affordability of rolling the method out more widely. The combination of room sensors, meteorological stations and room reservation data revealed the thermal comfort and air quality in four teaching room throughout the year 2016. The normative classification of comfort given by international standards is used to transfer the huge amount of data recorded into a vulgarised summary for the building occupants and landlord.

The following **conclusions** are drawn:

- The air quality measurements show a good ventilation strategy whatever the room and period. The air quality is clearly a strength of this building.
- The thermal comfort analysis depicted issues concerning overheating in summer and under heating in winter.
- A short period of measurement quickly highlighted problems that can be solved without any investment: increase of ventilation temperature set point (23°C instead of 21°C), modification of ventilation CO_2 threshold by the end of year 2015 (cut-in is 850ppm instead of 1000ppm).
- Despite the lack of thermal comfort measured, the data gathered shows that more than 85% of the occupancy time meets acceptable conditions in 2016.

These are some **perspectives** for future work on comfort measurement:

- Increase the number of probes per room (at least two) to have a better evaluation of both comfort and air quality as explained in §4.3.
- The occupancy considered is sometimes far from the real building occupancy, something must be done to handle more precisely this parameter.
- Include the landlord in the process of enhancing wellbeing of building users
- Measure the energy consumption in order to balance energy and comfort
- Especially in this building, compare the summer comfort rise since the installation of new roof top fan.

These are **recommendations** for improving this building comfort and feed back to users:

- The under heating issues can be solved by a better awareness of the use of the radiators thermostatic valve in the rooms by occupants (or hold the valve fully opened).
- The overheating can be tackled by investment on new solar protections, better control of ventilation (temperature based instead of CO_2 based ventilation), modifications of security rules (doors locked implies lack of natural ventilation heat-sink).
- Display real time comfort on the screen to better inform the users and notify possible issues. To do this, some technical barriers must be raise (e.g. automatic control of measurement failures due to power cut, centralisation of all data on a web server).
- To warn the user about his impact on comfort, some pieces of advices could be displayed on the TV screen about building comfort (thermostatic valve operation, door opening policy).

References

Airtesttechnologies.com. (2017). *EE80 sensor data sheet.* [online] Available at: http://www.airtesttechnologies.com/support/datasheet/EE80.pdf [Accessed 15 Dec. 2017].

Bureau of Standardisation NBN (2007), NBN EN 13779:2007, *Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning, 2nd edition,* Brussels :NBN

DIN German Institute for Standardization (2007) DIN V 18599-1 :2007, *Energy efficiency of buildings — Calculation of the energy needs, delivered energy and primary energy for heating, cooling, ventilation, domestic hot water and lighting*, Berlin : DIN

International Organization for Standardization (2005), ISO7730:2005, *Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria,* Geneva : ISO

International Well Building Institute pbc and Delos Living LLC (2017), *The Well Building Standard® v1 with Q4 2017 Addenda*, New York, Delos Living LLC

Lakrafli, H., 2008. *Application à différents outils de calcul de la ventilation du bâtiment académique de la F.U.L.,* Master Thesis, University of Liège

Ministry of Economy, Luxembourg (2010). *Règlement grand-ducal du 31 août 2010 concernant la performance énergétique des bâtiments fonctionnels*. Luxembourg: Legilux, pp.§3.1 & §7.
Available at: http://data.legilux.public.lu/eli/etat/leg/rgd/2010/08/31/n1/jo [Accessed 15 Dec. 2017].

Thomas, S. (2016). Visualisation monitoring Campus d'Arlon ULg. [online] Paper.dropbox.com. Available at: https://paper.dropbox.com/doc/Visualisation-monitoring-Campus-dArlon-ULg-AT06MFJAlVixGIkpJ3ojK [Accessed 15 Dec. 2017

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

The influence of building envelope design on the thermal comfort of high-rise residential buildings in Hong Kong

Yu Ting Kwok[1,*], Kevin Ka-Lun Lau[2,3,4], Edward Yan Yung Ng[1,2,3]

[1] School of Architecture, The Chinese University of Hong Kong
[2] Institute of Future Cities, The Chinese University of Hong Kong
[3] Institute of Environment, Energy and Sustainability, The Chinese University of Hong Kong
[4] CUHK Jockey Club Institute of Ageing, The Chinese University of Hong Kong
[*] ytkwok@link.cuhk.edu.hk

Abstract: Combined effects of climate change and rapid urbanisation make buildings in high-density cities vulnerable to overheating, and thus induce high cooling energy demand, especially during the more frequently occurring near-extreme conditions in summer. It is necessary to minimise building energy consumption without compromising the comfort of occupants by adopting climate-adaptive building envelope designs. By employing the summer reference year weather data for building simulations, this study examines how the indoor thermal comfort of free-running high-rise buildings in subtropical Hong Kong may be affected by modifications of the wall U-value, the depth of window overhang shading, and the window-to-wall ratio (WWR). Results show that better insulated flats experience less extreme thermal conditions but maintain a warmer-than-comfortable indoor environment, while flats with appropriate shading enjoy a net improvement in thermal comfort, especially for eastward and westward facing flats. When considering the WWR, thermal comfort can be maximised by placing windows strategically to facilitate cross-ventilation. Nevertheless, none of the models are able to achieve comfortable conditions for over 40% of the summertime. Further work is required to explore the potential of combined passive strategies or mixed-mode ventilation in optimising building performance and providing thermal comfort for occupants under future climate change.

Keywords: Building envelope design, Indoor thermal comfort, Building simulation, Summer reference year (SRY), High-rise residential buildings

1. Introduction

Indoor thermal comfort has long been an important area of research because of its well-established links with building occupants' well-being and health (Ortiz et al., 2017). As the urban population continues to grow worldwide, many cities are now dominated by high-density developments, with Hong Kong being a prime example where people commonly reside in high-rise apartment buildings. However, the indoor thermal environment of such compact living spaces is susceptible to overheating due to intense solar radiation, poor ventilation, and the slow release of heat from building materials, particularly during the hot and humid summers in Hong Kong. People thus rely heavily on air-conditioning to maintain thermal comfort, as reflected by the continued increase in electricity consumption by the domestic sector (HKCSD, 2016). The more frequent occurrence of extreme hot weather brought by climate change further exacerbates the urban heat island effects and incurs higher energy demand. In order to minimise energy consumption without compromising the comfort of occupants, there is an obvious need to optimise building performance by adopting climate-adaptive building design strategies.

Multiple efforts have been made by the local government and research communities to improve energy efficiency in high-rise residential buildings in Hong Kong (Ma and Wang, 2009). Modifications on glazing and wall insulation (Bojic et al., 2001; Cheung et al., 2005; Bojic and Yik, 2007) have been investigated in earlier studies, while others have explored the use of intelligent building control systems to balance comfort and energy use (Shaikh et al., 2014). In hot and humid climates, solar heat gain from total window area and heat transfer through building façades were found to have the most considerable effects on building energy performance (Yildiz and Arsan, 2011), as is the case for Hong Kong (Chen et al., 2015). In the last two decades, Building Energy Codes were introduced by the Hong Kong Government (Chan and Yeung, 2005) to regulate energy use in buildings, including the mandatory control on Overall Thermal Transfer Values, which recognizes the importance of managing outdoor-to-indoor heat transfer through the external envelope of buildings (Lam et al., 2005). Concurrently, the Hong Kong Building Environmental Assessment Method (BEAM) was initiated by the private sector to promote environmental friendly building designs, construction, operation, and management. An alternative passive design route for buildings to achieve credits for certification by considering site aspects, daylighting, natural ventilation, envelope heat transfer etc., was recently made available (BEAM Society Limited, 2012; Chen et al., 2015). There have also been an increasing number of studies on the effectiveness of passive design strategies and naturally ventilated buildings in Hong Kong (Haase and Amato, 2009; Gao and Lee, 2011; Chen et al., 2017). Nevertheless, few focused on the more fundamental relationship between building envelope parameters and thermal comfort of indoor environments under free-running conditions, nor have the added warming effects of climate change been taken into account in previous parametric studies.

In light of the knowledge gap identified, this study aims to examine how modifications of various building envelope parameters correlate with measures of indoor thermal comfort under near-extreme summer conditions in hot and humid Hong Kong. The responses for flats of different orientations will also be investigated. A brief discussion on the effectiveness and limitations of various design strategies for high-rise residential buildings will then be presented.

2. Methodology

This study was conducted by performing building simulations with EnergyPlus on the DesignBuilder software platform. EnergyPlus is a dynamic simulation engine used by the Department of Energy in the United States for internationally recognized building assessments and its robustness have been well-validated by field measurements (Shrestha and Maxwell, 2011; Mateus et al., 2014) as well as the Building Energy Simulation TEST procedure (Judkoff and Neymark, 1995). Hourly weather data of the Summer Reference Year (SRY) of Hong Kong, which has been statistically adjusted from the Test Reference Year to represent near-extreme summer conditions (Lau et al., 2017), were used as inputs for the building simulations. Results for the three hottest summer months, from June to August, were then extracted from annual simulations for subsequent analyses.

2.1. Baseline building model

Public rental housing (PRH) accommodates around half of the total population in Hong Kong (HKHA, 2016), and cross-shaped buildings with 40 or more storeys are common in newer generation PRH estates. Therefore, the baseline building model was constructed based on the Concord type PRH, as shown in Figure 1a. Windows were assumed to have a height (sill to head) of 1.9m. To reduce the computational cost required, the building layout was simplified to eight identical flats and only the living rooms and bedrooms were included in thermal calculations of flats (Figure 1b). Furthermore, as the middle floor is considered sufficient to represent the average performance of a high-rise building (Chen et al., 2015), the rest of the building was constructed using adiabatic component blocks.

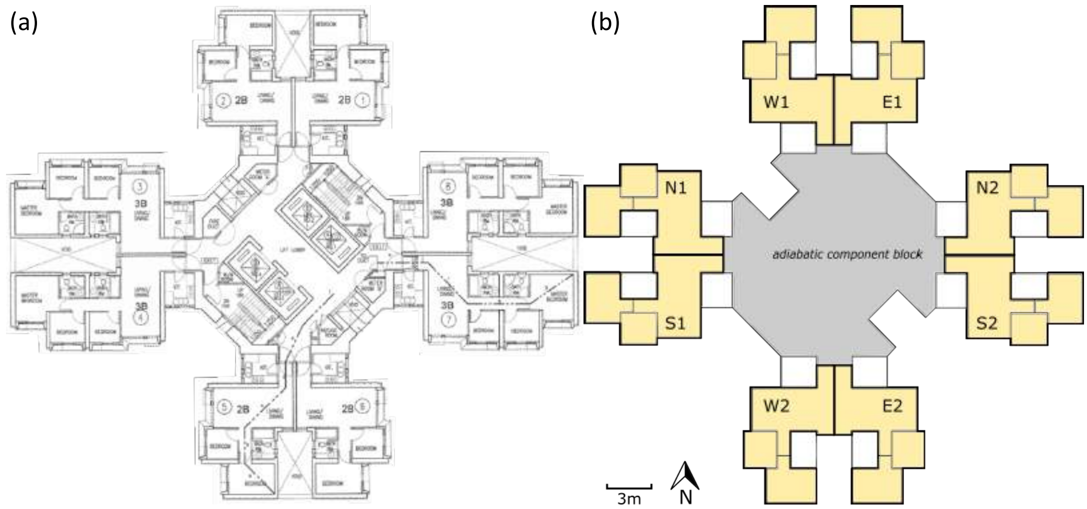


Figure 1. (a) Building layout plan of a Concord type PRH and (b) a simplified layout used for building simulation (only the parts highlighted in yellow were considered in thermal calculations). Flats facing different orientations are labelled accordingly.

Building model properties were set according to the BEAM Plus New Buildings Version 1.2 manual (BEAM Society Limited, 2012). Table 1 shows the detailed characteristics of the construction materials. The window-to-wall ratio (WWR) for baseline residential buildings was defined to be 0.4. The building occupancy schedule was set according to survey findings by Chen and Lee (2010) and an occupant density of 0.083 people/m^2 was adopted to reflect typical high-density living conditions in public housing estates in Hong Kong (HKHA, 2016). As this study focuses only on the effects of passive designs under free-running conditions and not the heating, ventilation and air conditioning (HVAC) systems of buildings, the windows were assumed to be 30% opened all the time regardless of outdoor temperatures and no mechanical ventilation was applied.

Table 1. Properties of construction materials for the building envelope of the baseline building model, where k is thermal conductivity, ρ is density, C_p is specific heat, α is solar absorptivity of exposed surface (adapted from BEAM Society Limited, 2012).

	Thickness (m)	Material	k (W/mK)	ρ (kg/m^3)	C_p (J/kgK)	α (-)
External Walls						
Layer 1 (exterior)	0.005	Mosaic Tiles	1.5	2500	840	0.58
Layer 2	0.01	Cement/Sand Plastering	0.72	1860	840	
Layer 3	0.1	Heavy Concrete	2.16	2400	840	
Layer 4 (interior)	0.01	Gypsum Plastering	0.38	1120	840	0.65
Floor/Ceiling (middle floor flats)						
Layer 1	0.01	Gypsum Plasterboard	0.38	1120	837	
Layer 2	0.18	Reinforced Concrete	1.9	2300	840	
Layer 3	0.01	Floor Tiles	0.8	1700	850	
Windows						
Layer 1	0.006	Tinted Glass	1.05	2500	840	0.65

2.2. Building envelope parameters

The majority of heat gain or loss of a building is contributed by the building envelope, which functions to protect and moderate the climate of the indoor environment (Mirrahimi et al., 2016). It comprises the external wall, roof, floor, glazing, and shading, and the amount of heat transfer is dependent on the physical building form and design, as well as its orientation. Lam et al. (2005) identified solar heat gain through windows as the dominant source of heat gain for buildings in subtropical Hong Kong. Reducing window areas and employing appropriate shading devices may be effective in minimising the direct solar radiation indoors and hence improve internal thermal conditions (Al-Tamimi and Fadzil, 2011). Window designs were also found to perform better on the west and east orientations, and the worst for windows facing north (Huang et al., 2014). Besides, previous research showed that thinner external walls with higher U-values are less capable of regulating indoor temperatures, resulting in more intense and longer durations of discomfort felt by occupants (Kwok et al., 2017).

Impacts of construction material properties, window sizes, and shading devices on the indoor thermal comfort of naturally-ventilated buildings in hot-humid climates have often been investigated (Wang and Wong, 2007). With an understanding of the significant components of a building envelope, selected parameters, namely the wall U-value, the depth of window overhang shading, and the WWR, were modified separately on the baseline building model of Hong Kong. The various configurations evaluated in this study are listed in Table 2.

Table 2. Details of the building envelope parameters studied.

Model	Wall U-value (W/m^2K) *concrete thickness (m)*	Depth of overhang shading (m)	Window-to-wall ratio (-)
BL[a]	3.849 *(0.1)*	0	0.4
U15	3.534 *(0.15)*	0	0.4
U20	3.267 *(0.2)*		
U25	3.037 *(0.25)*		
U30	2.837 *(0.3)*		
O03	3.849 *(0.1)*	0.3	0.4
O06		0.6	
O09		0.9	
O12		1.2	
O15		1.5[b]	
Rmin	3.849 *(0.1)*	0	0.033[c]
R01			0.1
R02			0.2
R03			0.3

a. baseline model (BL) constructed according to BEAM Plus New Buildings Version 1.2 manual (BEAM Society Limited, 2012)

b. based on guidelines for effective shading that overhanging projection should be equal to or less than 1.5m from the external wall surface (HKBD, 2014)

c. based on statutory requirement in APP-130 that total area of primary openings should not be less than 1/16 of the floor area of the room (HKBD, 2016)

2.3. Measures of thermal comfort

The indoor thermal comfort was described using the Predicted Mean Vote (PMV) index (Fanger, 1970) and operative temperatures (T_{op}). Human thermal sensations from very cold (-3) to very hot (+3) were calculated within DesignBuilder according to the ISO standard 7730 (2005), with the metabolic rate and clothing index assumed to be 0.9 met and 0.3 clo, respectively. As a result of acclimatisation, people living in hot-humid climates have often reported neutral temperatures higher than that predicted by the PMV model (Djamila et al., 2013). To account for such a discrepancy, an extended PMV model incorporating an expectancy factor ‘e’ was developed for predicting the actual votes of occupants living in non-air-conditioned buildings in warm climates (Fanger and Toftum, 2002). This approach has previously been applied with e = 0.7 for evaluating the thermal comfort of PRH flats in Hong Kong (Kwok et al., 2017). Throughout this study, positive PMV values were also multiplied by an expectancy factor of 0.7. On the other hand, T_{op} was used to reflect the physical thermal environment felt by occupants within a flat. T_{op} was preferred as a measure of thermal comfort as it is able to represent effects of both convective and radiative heat transfer. For occupants with sedentary behaviours who are not exposed to direct sunlight and strong air flow, T_{op} can be approximated by the averaging the simulated air and radiant temperatures (ASHRAE Standard, 2004).

3. Results

3.1. Baseline model and effects of building orientation

Operative temperatures (T_{op}) for each hour of the day, averaged over simulation results from June to August of the SRY, are plotted in Figure 2 to show the diurnal variations of T_{op} for flats facing different orientations (refer to Figure 1 for the labelling of flats). Flats facing the east (E1, E2) and the west (W1, W2) generally exhibit higher T_{op} due to direct solar radiation from the low angle sun during sunrise and sunset. Eastward facing flats warm up the fastest in the day, while westward facing flats have the highest T_{op} in the late afternoon and remain the hottest throughout the night. Flats facing the west reach the highest average daily maximum T_{op} (up to 31.4°C) at around 6pm, which is over 0.6°C higher than that of flats facing the north or the south. A similar diurnal variation pattern and a relatively small daily temperature range can be observed for all northward and southward facing flats (N1, N2, S1, S2).

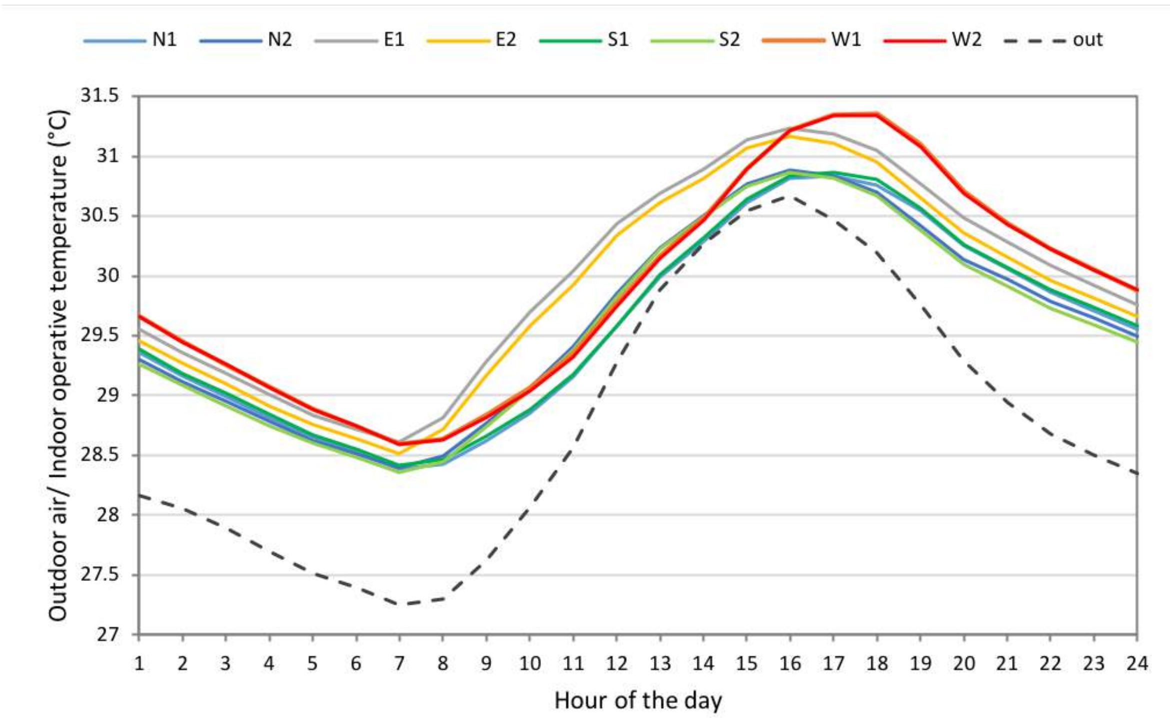


Figure 2. Diurnal variations of outdoor air temperature and T_{op} for flats facing different orientations in the baseline building model, averaged over June to August of the SRY.

Figure 3 shows the predicted thermal sensations of occupants and their corresponding amount of time felt in flats of different orientations in the baseline building model. PMV values were calculated based on the adjusted PMV model with e = 0.7. Since flats were simulated under free-running conditions, highly variable indoor thermal environments from PMV less than -0.5 (slightly cold to cold) to more than +2 (very hot) can be observed. Occupants feel warm to hot (PMV +0.5 to +1.5) for the majority of time during a near-extreme summer in Hong Kong. Flats of northern and southern orientations provide comfortable thermal conditions (PMV -0.5 to +0.5) for around 30% of the time, whereas occupants in flats of eastern and western orientations are only comfortable for around 25% of the time. The latter are even exposed to very hot conditions (PMV +1.5 or above) up to 16% of the time and should be given particular attention when designing for indoor thermal comfort. Therefore, the following parametric analyses will mainly focus on flats facing the east (E flats) and the west (W flats).

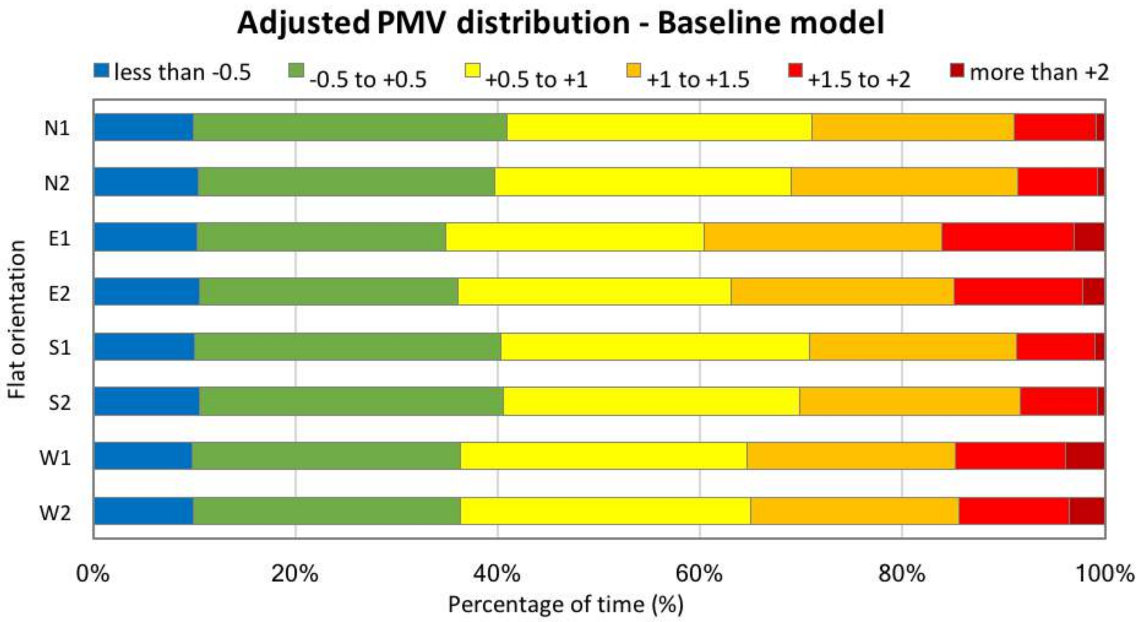


Figure 3. Adjusted PMV (e=0.7) distribution for flats facing different orientations in the baseline building model over June to August in the SRY.

3.2. Effects of wall U-value

The effects of altering the thickness of the concrete layer, and thus the U-value, of the external wall on the indoor thermal comfort are investigated for E flats and W flats (Figure 4). U-value is a measure of heat transfer rate and walls with a lower U-value are able to resist heat flow and provide better insulation for the indoor environment. By reducing the external wall U-value, the proportion of extreme discomfort hours (both very hot and cold) is reduced. The amount of time when occupants experience a PMV of more than +2 is nearly halved for both E flats and W flats. However, occupants do not enjoy more comfort hours (PMV -0.5 to +0.5). Instead, occupants feel warm to hot (PMV +0.5 to +1.5) for a longer duration of time in summer, with the proportion of time having a PMV of +1 to +1.5 reaching almost 30% in E flats for the U30 model.

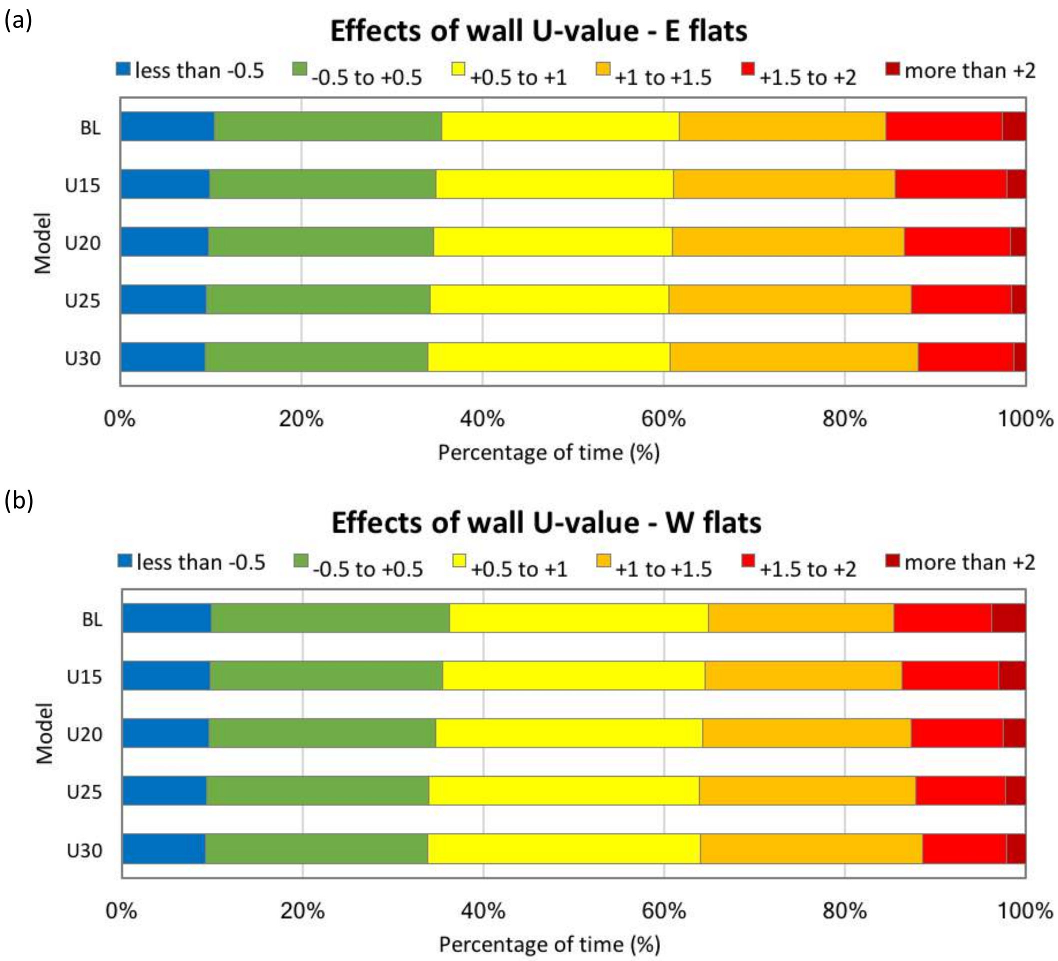


Figure 4. Effects of external wall U-value on the adjusted PMV (e=0.7) distribution for (a) E flats and (b) W flats over June to August in the SRY.

The maximum and median T_{op} for E flats and W flats are plotted against wall U-values in Figure 5a. A positive and roughly linear relationship can be seen for maximum T_{op} and wall U-values, but median T_{op} remain largely constant for different wall U-values. Reducing the wall U-value is also able to narrow the T_{op} range experienced by building occupants during summer (Figure 5b). The effect is more prominent for W flats where the T_{op} range for model U30 is up to 10% smaller than the baseline scenario.

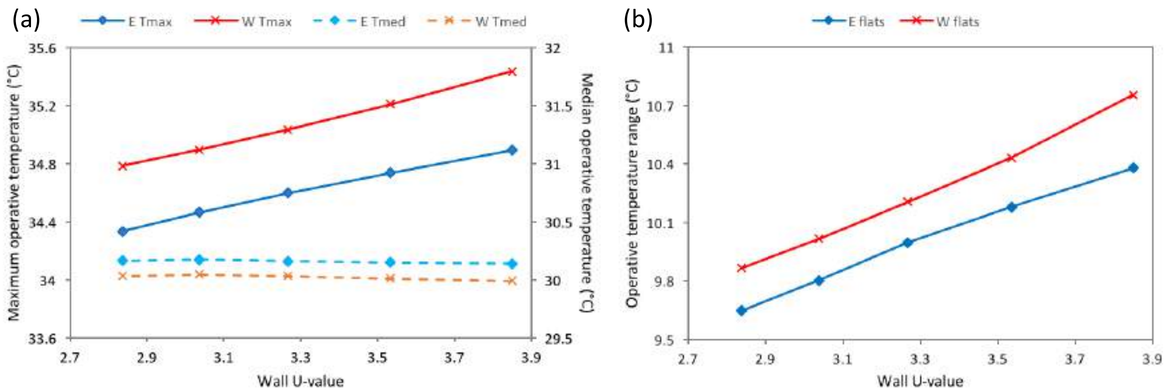
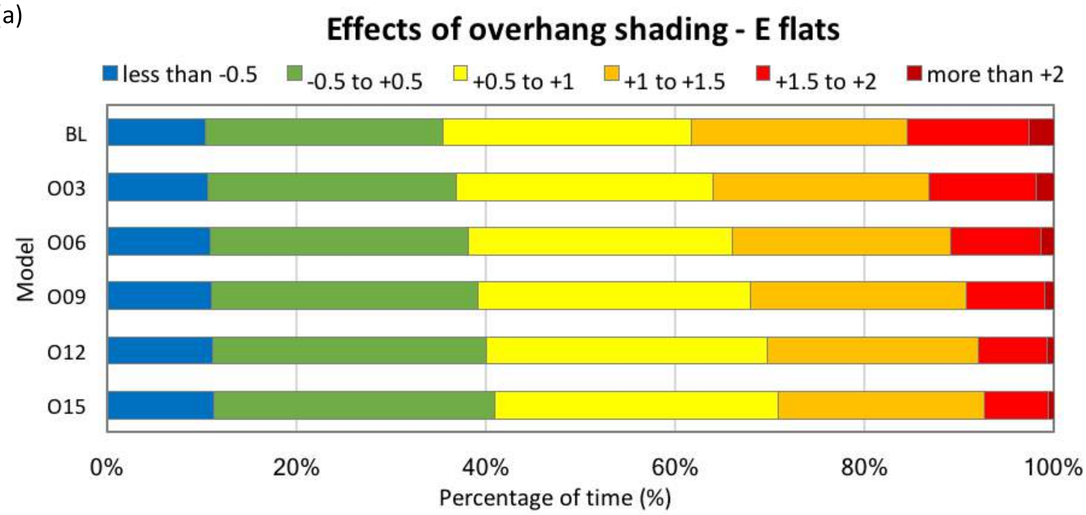


Figure 5. Relationships between external wall U-values and (a) maximum and median T_{op} and (b) T_{op} range for E flats and W flats.

3.3. Effects of window shading

A net cooling effect is achieved by providing overhang shading to windows. As seen in Figure 6, the thermal comfort of the indoor environment improves with increasing depth of the overhang shading for both E flats and W flats. Comparing the O15 model to the baseline scenario, the amount of time when occupants in free-running flats feel comfortable (PMV -0.5 to +0.5) increases by around 5% during the SRY. While occupants may feel cold for a similar amount of time with or without window shading, the proportion of hot to very hot hours (PMV +1.5 or above) is reduced significantly, with almost no time having a PMV of more than +2 for the O15 model.

(a)



(b)

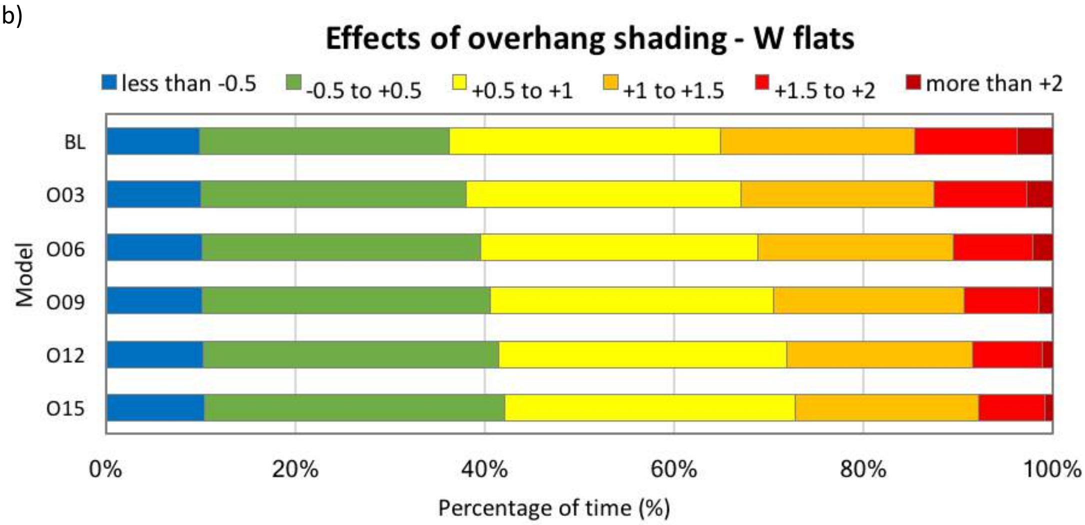


Figure 6. Effects of depth of window overhang shading on the adjusted PMV (e=0.7) distribution for (a) E flats and (b) W flats over June to August in the SRY.

By looking at the maximum and median T_{op}, a non-linear and negative relationship is found between T_{op} and depths of overhang shading (Figure 7). The rate of T_{op} reduction gradually decreases as the length of overhang extends outwards from the external wall. Comparing the scales in Figures 7a and 7b, the magnitude of cooling by shading is found to be more prominent for the extremely hot conditions (represented by maximum T_{op}), especially for W flats. Also, consistent with previous findings by Huang et al. (2014), this design strategy also performs better for E flats and W flats than for N/S flats, as inferred from the steeper slopes of the curves in Figure 7.

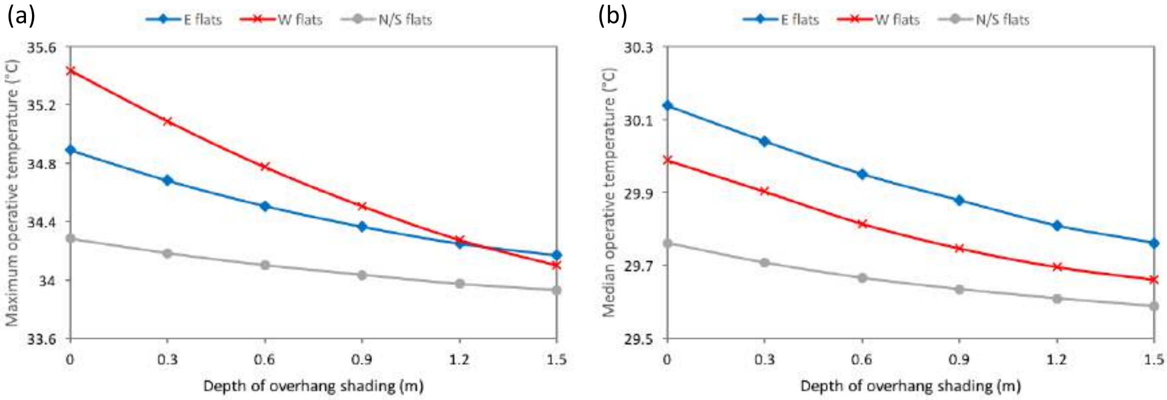


Figure 7. Relationships between depths of window overhang shading and (a) maximum T_{op} and (b) median T_{op} for E flats, W flats, and N/S flats.

3.4. Effects of window-to-wall ratio

Figure 8 shows the PMV distributions of models with different WWRs for E flats and W flats. The model having the minimum WWR of 0.033 performs the worst. Occupants may feel too warm (PMV higher than +0.5) for more than 80% of the summer time, with up to a third of which being PMV +1.5 or above for E flats. The amount of time within the comfort range (PMV -0.5 to +0.5) is only around 15%. When WWR is increased to 0.1, the indoor thermal conditions improve significantly. As WWR continues to increase, the amount of time within the comfort range also increases, but so does the proportion of very hot conditions with PMV +1.5 or above, except for when WWR increases to 0.4 in the BL model.

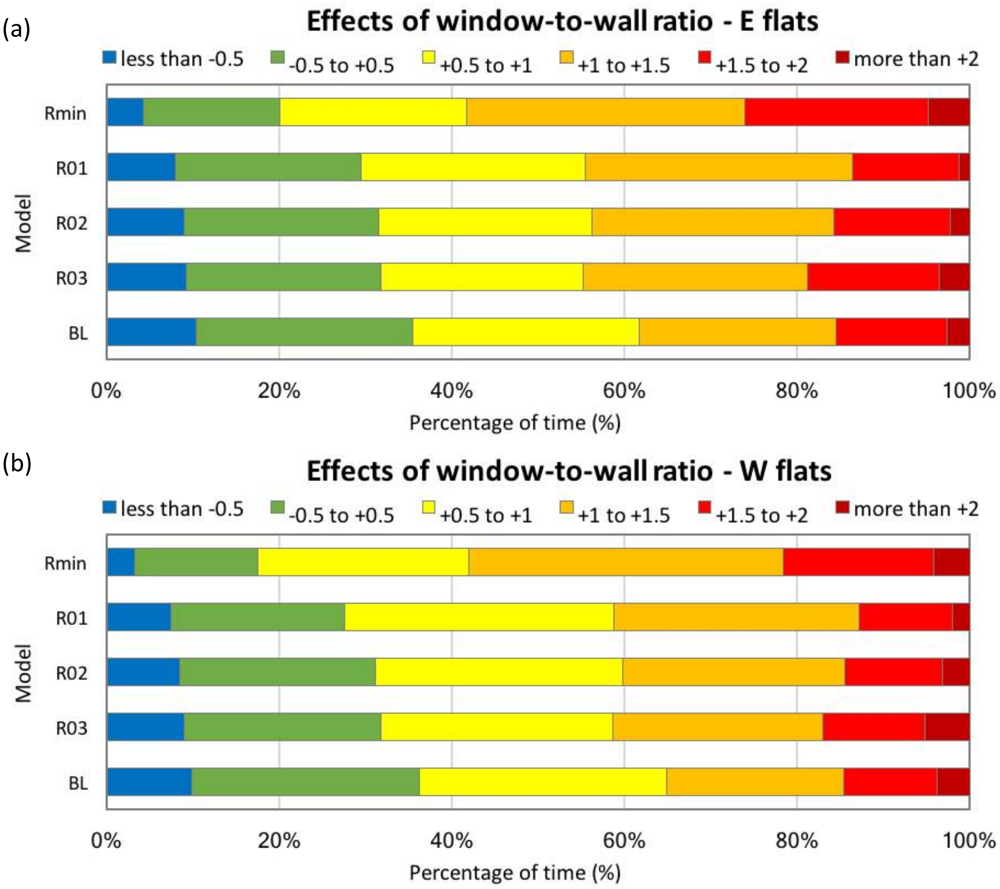


Figure 8. Effects of window-to-wall ratio on the adjusted PMV (e=0.7) distribution for (a) E flats and (b) W flats over June to August in the SRY.

With reference to Figure 9a, to minimise discomfort due to extreme hotness, which can be represented by the maximum T_{op}, an optimum condition is found when WWR is 0.1. Maximum T_{op} then increases by around 0.5°C for each 0.1 increase in WWR. Median and minimum T_{op} display a different trend (Figure 9b). It is the hottest for the Rmin model, and both median and minimum T_{op} do not vary much for flats with WWR of 0.1 to 0.3. A slight drop in overall T_{op} is observed in flats of all orientations (N and S flats not shown) for the baseline model with a WWR of 0.4. This may be due to cross-ventilation made possible by extra windows, and will be further discussed in Section 4.3.

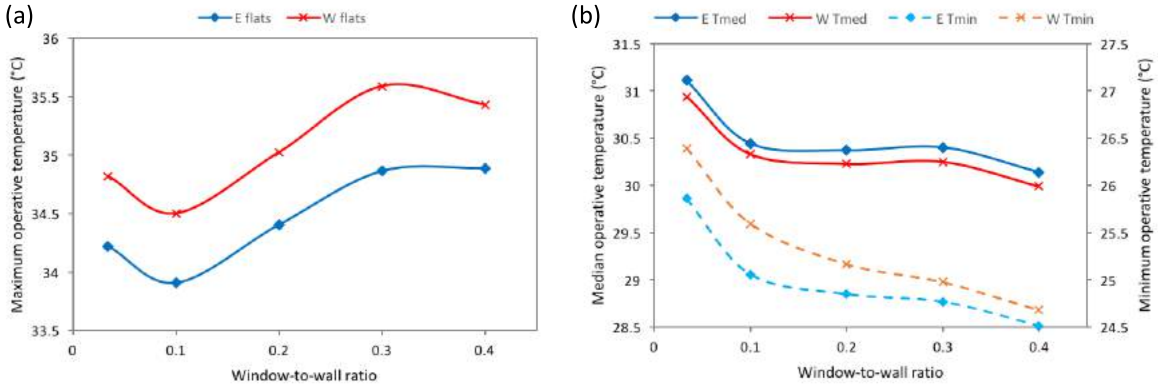


Figure 9. Relationships between window-to-wall ratios and (a) maximum T_{op} and (b) median and minimum T_{op} for E flats and W flats.

4. Discussion

4.1. Suitability of building insulation

Better insulated building envelopes are able to maintain a less variable indoor thermal environment. It is effective for narrowing the temperature range experienced by building occupants (Figure 5b). Reducing the external wall U-value reduces the duration of extreme discomfort indoors, both too cold and too hot (Figure 4). It can also save the energy required for mechanical cooling (Kwok et al., 2017). Building insulation is a crucial design element for buildings in temperate climates due to the wide annual temperature range and longer winter period (Yilmaz, 2007). London dwellings have typical wall U-values of 2.1 W/m^2K or even lower for newer or retrofitted buildings (Mavrogianni et al., 2012). However, in subtropical Hong Kong, results reveal potential overheating problems for flats with thicker walls and better insulation under free-running conditions in a near-extreme summer. Although extremely hot or cold conditions become less likely indoors, occupants may generally feel warm to hot for a greater proportion of time. Therefore, when applying insulation to high-rise residential buildings in hot and humid climates like in Hong Kong, it is important to strike a balance between building energy efficiency and the thermal comfort of those who may not be able to afford the high costs of air-conditioning.

4.2. Effective shading strategies

Providing overhang shading to windows results in a net improvement of the indoor thermal comfort of high-rise residential buildings in Hong Kong during near-extreme summer conditions (Figure 6). T_{op} in flats are effectively reduced as shading devices control the amount the direct solar radiation entering flats, especially for those facing the east or the west (Figure 7). Nevertheless, the flattening curves suggest that shading may no longer be effective after reaching a certain depth of overhang.

Another advantage of shading over other passive design strategies is its ease of implementation on existing buildings. They could be added to the standard PRH buildings, which are constructed from pre-moulded blocks, and could also be tailored for windows facing different orientations. Moreover, the use of other shading devices, such as vertical shading or side-fin projections, and egg-crate shading, could be explored to maximise the potential for temperature reduction (Al-Tamimi and Fadzil, 2011). Besides shading windows, shading external wall areas by erecting horizontal or vertical panels could also be an innovative and cost-effective solution to reduce heat uptake and transmittance through external walls into the interior of flats.

4.3. WWR requirement and cross-ventilation

According to the building regulations of Hong Kong, primary openings in a room should not be less than 1/16 of the floor area of the room (HKBD, 2016). This converts to a WWR of 0.033 for the building model used in this study. However, results present unreasonably hot indoor conditions for the model with minimum WWR. Occupants of all flats feel too warm (PMV higher than +0.5) for at least 80% of the time in a near-extreme summer (Figure 8, N and S flats not shown). An increase of the statutory minimum window area requirement could thus be recommended in light of these findings.

Cross-ventilation facilitates air movements across the indoor space and is particularly important for the thermal comfort of buildings in hot-humid climates (Givoni, 1994). Previous studies confirmed that better ventilation performance can be achieved by having two sets of openings placed opposite or perpendicular to each other (Gao and Lee, 2011). Unfortunately, most PRH flats in Hong Kong have windows positioned only on one side of the flat owing to the compact design and limited flat size. In the models of this study, windows were constructed based on the Concord type PRH layout with primary openings all facing the same orientation. For models with a higher WWR, secondary openings were added after the widths of primary openings have reached the full length of the primary façade (Figure 10). This potentially allows for cross-ventilation to occur, which is likely the reason for the improvement in indoor thermal comfort (Figure 8), as well as the slight drop in T_{op} observed (Figure 9). Therefore, in addition to the size of window openings, attention should also be given to how windows are positioned when optimising flats for thermal comfort under free-running conditions. To fully examine the effects of cross-ventilation, further studies using computational fluid dynamic (CFD) models would be required.

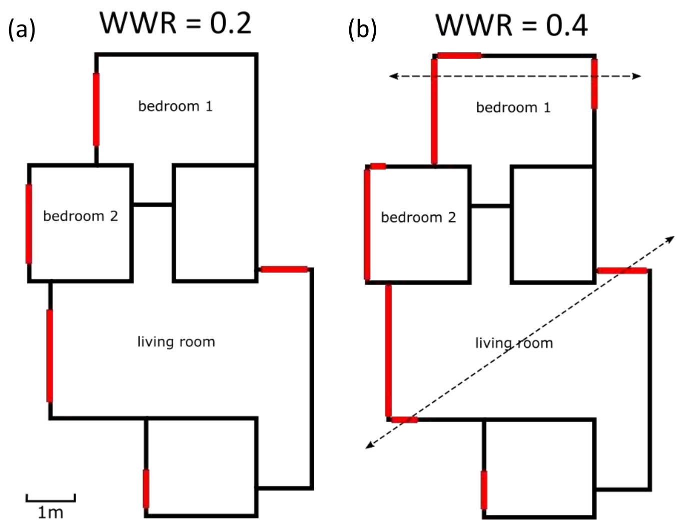


Figure 10. Floor layout and window positions (in red) of flat W1 in model (a) R02 and (b) BL. Arrows show potential cross-ventilation air movements.

4.4. Limitations of passive design strategies

Although careful design of the building envelope may improve the indoor thermal conditions of flats, none of the models examined were able to provide occupants with a thermally comfortable indoor environment (PMV -0.5 to +0.5) for more than 40% of the time during a near-extreme summer in Hong Kong. With rising outdoor temperatures, as well as more frequent heat wave events due to climate change, passive design alone is insufficient to help occupants in free-running buildings mitigate the indoor thermal discomfort. It is inevitable for occupants to adapt by using mechanical cooling such as fans and air-conditioning. Minimising cooling energy consumption while maximising indoor thermal comfort should be the goal for building optimisation research. This would require a tactful combination of improvement in building energy efficiency, HVAC system controls for mixed-mode ventilation, and most importantly, the design of the building itself.

5. Conclusion

In this study, the influence of three building envelope parameters, namely the wall U-value, the depth of window overhang shading, and the WWR, on the indoor thermal comfort of high-rise apartment flats under free-running conditions in subtropical Hong Kong has been investigated. Particular attention has been paid to take into account the more frequent near-extreme summer conditions due to climate change by employing the SRY weather data in building simulations. The varied effects for flats facing different orientations have also been evaluated.

Flats with lower wall U-values, and thus better insulation, have a less variable indoor thermal environment. Although extreme indoor conditions become less likely, occupants may feel generally warmer for a longer duration of time in summer. Overheating thus remain as a concern for well-insulated buildings in hot-humid climates. Window overhang shading induces a net improvement in the thermal comfort of flats, more notably for those facing the east or the west. It is also a cost-effective strategy which can be easily applied onto existing buildings. The minimum WWR required by current regulations results in unreasonably hot thermal conditions and should be revised accordingly. Besides identifying an optimal size for openings, they should also be placed to allow for cross-ventilation, which can further maximise the thermal comfort of flats under free-running conditions.

This study only serves to provide initial findings on how various building envelope parameters correlate independently with the indoor thermal comfort of high-rise residential buildings in subtropical climates. Further research is required to examine their combined effects and the optimisation of building performance using mixed-mode ventilation. The accuracy and reliability of simulation results could also be enhanced by validation with field measurements during heat wave episodes. Moreover, effective passive design strategies identified, such as shading and cross-ventilation, could be investigated in more detail by coupling thermal simulations with daylighting and CFD models. The combined findings are expected to contribute to the formulation of practical guidelines which could help engineers and architects design living spaces capable of providing thermal comfort and mitigating climate change.

Acknowledgements

This work was supported by the General Research Fund from the Research Grants Council of Hong Kong (grant number 14603715) and the Vice-Chancellor Discretionary Fund, The Chinese University of Hong Kong. Data for the development of the SRY weather file were provided by Mr P.W. Chan from the Hong Kong Observatory.

References

Al-Tamimi, N.A. & Fadzil, S.F.S. 2011, The potential of shading devices for temperature reduction in high-rise residential buildings in the tropics, *Procedia Engineering*, 21, pp 273-282.

ASHRAE Standard 2004, Standard 55-2004, Thermal environmental conditions for human occupancy.

BEAM Society Limited 2012, BEAM Plus New Buildings Version 1.2, Hong Kong.

Bojic, M., Yik, F. & Sat, P. 2001, Influence of thermal insulation position in building envelope on the space cooling of high-rise residential buildings in Hong Kong, *Energy and Buildings*, 33(6), pp 569-581.

Bojic, M. & Yik, F. 2007, Application of advanced glazing to high-rise residential buildings in Hong Kong, *Building and Environment*, 42(2), pp 820-828.

Chan, A.T. & Yeung, V.C. 2005, Implementing building energy codes in Hong Kong: energy savings, environmental impacts and cost, *Energy and Buildings*, 37(6), pp 631-642.

Chen, H. & Lee, W.L. 2010, Combined space cooling and water heating system for Hong Kong residences, *Energy and Buildings*, 42(2), pp 243-250.

Chen, X., Yang, H. & Lu, L. 2015, A comprehensive review on passive design approaches in green building rating tools, *Renewable and Sustainable Energy Reviews*, 50, pp 1425-1436.

Chen, X., Yang, H. & Wang, Y. 2017, Parametric study of passive design strategies for high-rise residential buildings in hot and humid climates: miscellaneous impact factors, R*enewable and Sustainable Energy Reviews*, 69, pp 442-460.

Chen, X., Yang, H. & Zhang, W. 2015, A comprehensive sensitivity study of major passive design parameters for the public rental housing development in Hong Kong, *Energy*, 93, pp 1804-1818.

Cheung, C.K., Fuller, R.J. & Luther, M.B. 2005, Energy-efficient envelope design for high-rise apartments, *Energy and Buildings*, 37(1), pp 37-48.

Djamila, H., Chu, C. & Kumaresan, S. 2013, Field study of thermal comfort in residential buildings in the equatorial hot-humid climate of Malaysia, *Building and Environment*, 62, pp 133-142.

Fanger, P.O. & Toftum, J. 2002, Extension of the PMV model to non-air-conditioned buildings in warm climates, *Energy and Buildings*, 34(6), pp 533-536.

Fanger, P.O. 1970, Thermal comfort. Analysis and applications in environmental engineering. Copenhagen: Danish Technical Press.

Gao, C. & Lee, W. 2011, Evaluating the influence of openings configuration on natural ventilation performance of residential units in Hong Kong, *Building and Environment*, 46(4), pp 961-969.

Givoni, B. 1994, Building design principles for hot humid regions, *Renewable Energy*, 5(5-8), pp 908-916.

Haase, M. & Amato, A. 2009, An investigation of the potential for natural ventilation and building orientation to achieve thermal comfort in warm and humid climates, *Solar Energy*, 83(3), pp 389-399.

Hong Kong Buildings Department (HKBD) 2016, Practice Note for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers APP-130 Lighting and Ventilation Requirements – Performance-based Approach.

Hong Kong Buildings Department (HKBD) 2014, Guidelines on Design and Construction Requirements for Energy Efficiency of Residential Buildings.

Hong Kong Census and Statistics Department (HKCSD) 2016, Hong Kong Energy Statistics Annual Report.

Hong Kong Housing Authority (HKHA) 2016, Housing in Figures 2016.

Huang, Y., Niu, J. & Chung, T. 2014, Comprehensive analysis on thermal and daylighting performance of glazing and shading designs on office building envelope in cooling-dominant climates, *Applied Energy*, 134, pp 215-228.

ISO Standard 2005, 7730. Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, International Organization for Standardization: Geneva, Switzerland.

Judkoff, R. & Neymark, J. 1995, International Energy Agency building energy simulation test (BESTEST) and diagnostic method.

Kwok, Y.T., Lai, A.K.L., Lau, K.K., Chan, P.W., Lavafpour, Y., Ho, J.C.K. & Ng, E.Y.Y. 2017, Thermal comfort and energy performance of public rental housing under typical and near-extreme weather conditions in Hong Kong, *Energy and Buildings*, 156, pp 390-403.

Lam, J.C., Tsang, C., Li, D.H. & Cheung, S. 2005, Residential building envelope heat gain and cooling energy requirements, *Energy*, 30(7), pp 933-951.

Lau, K.K., Ng, E.Y., Chan, P. & Ho, J.C. 2017, Near-extreme summer meteorological data set for sub-tropical climates, *Building Services Engineering Research and Technology*, 38(2), pp 197-208.

Ma, Z. & Wang, S. 2009, Building energy research in Hong Kong: a review, *Renewable and Sustainable Energy Reviews*, 13(8), pp 1870-1883.

Mateus, N.M., Pinto, A. & da Graça, G.C. 2014, Validation of EnergyPlus thermal simulation of a double skin naturally and mechanically ventilated test cell, *Energy and Buildings*, 75, pp 511-522.

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P. & Oikonomou, E. 2012, Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings, *Building and Environment*, 55, pp 117-130.

Mirrahimi, S., Mohamed, M.F., Haw, L.C., Ibrahim, N.L.N., Yusoff, W.F.M. & Aflaki, A. 2016, The effect of building envelope on the thermal comfort and energy saving for high-rise buildings in hot–humid climate, *Renewable and Sustainable Energy Reviews*, 53, pp 1508-1519.

Ortiz, M.A., Kurvers, S.R. & Bluyssen, P.M. 2017, A review of comfort, health, and energy use: Understanding daily energy use and wellbeing for the development of a new approach to study comfort, *Energy and Buildings*, 152, pp 323-335.

Shaikh, P.H., Nor, N.B.M., Nallagownden, P., Elamvazuthi, I. & Ibrahim, T. 2014, A review on optimized control systems for building energy and comfort management of smart sustainable buildings, *Renewable and Sustainable Energy Reviews*, 34, pp 409-429.

Shrestha, S. & Maxwell, G. 2011, Empirical validation of building energy simulation software: EnergyPlus, *Proceedings of Building Simulation*, pp 2935.

Wang, L. & Wong, N.H. 2007, The impacts of ventilation strategies and facade on indoor thermal environment for naturally ventilated residential buildings in Singapore, *Building and Environment*, 42(12), pp 4006-4015.

Yıldız, Y. & Arsan, Z.D. 2011, Identification of the building parameters that influence heating and cooling energy loads for apartment buildings in hot-humid climates, *Energy*, 36(7), pp 4287-4296.

Yılmaz, Z. 2007, Evaluation of energy efficient design strategies for different climatic zones: Comparison of thermal performance of buildings in temperate-humid and hot-dry climate, *Energy and Buildings*, 39(3), pp 306-316.

An Exergetic Investigation on the Effect of Long-term Thermo-physical Exposure on Thermal Perception

Masanori Shukuya[1], Rinto Nagai[2] and Hom B. Rijal[1]

[1] Dept. of Restoration Ecology and Built Environment, Tokyo City University, Japan;
[2] Kumahira Co. Ltd. (Former Graduate Student of Tokyo City University)

Abstract: People are exposed to ever-changing thermal environment. In due course they subconsciously develop their respective perception and cognition. With such general fact in mind, we designed a two-stage subjective experiment focusing on hot and humid summer weather in Yokohama, Japan, and analysed the experimental results from the exergetic viewpoint. At the first stage experiment, thirty-eight subjects were asked to carry grey-coloured globe-temperature sensors and others for one week. At the follow-up second stage experiment, we asked them to visit and stay for a while in three rooms of different thermal conditions, and to answer their thermal preference and cognitive temperature. The subjects were divided into two groups according to their thermal history. Their perception and thermal history were then investigated in terms of human-body exergy consumption rate and also thermal radiant exergy, to which they were exposed in naturally ventilated and mechanically conditioned rooms. The relationship between the human-body exergy consumption rate and the preference votes made by the two groups were not different much, but there was a distinctive difference with respect to thermal radiant exergy input rate. The result suggests that the thermo-physical exposure becomes the memory of thermal history and it affects their respective thermal perception.

Keywords: Thermal history, perception, radiant exergy, exergy consumption rate, cognitive temperature

1. Introduction

People are exposed to ever-changing thermal environment here and there indoors and outdoors. In due course they subconsciously develop ceaselessly their respective perception and cognition. With such general facts in mind, we designed a two-stage subjective experiment focusing on the hot and humid summer weather in Yokohama, Japan, and analysed the experimental results in particular from the exergetic viewpoint. At the first stage experiment, thirty-eight subjects were asked to carry grey-coloured globe-temperature sensors and others for one week. At the follow-up second stage experiment, we asked them to visit and stay for a while in three rooms of different thermal conditions, and to answer their thermal preference and cognitive temperature. The subjects were divided into two groups according to their thermal history characterized from the first-stage experiment.

Their perception and thermal history was then investigated in terms of human-body exergy consumption rate and also thermal radiant exergy, to which they were exposed in the three rooms. The analyses were made in particular focussing on whether thermo-physical exposure in the past becomes the memory of thermal history and, if there is such thermal history to be taken into consideration, how it affects the thermal perception of people.

2. Exergy approach

Research on the built environment with exergetic viewpoint has been grown to the present status since mid-1990s. In due course, the understanding of exergy concept itself has advanced and been sharpened to a large extent so that it can be fully applied to the field of building science, in particular, indoor thermal environmental science. The essence of exergy concept is that it explicitly indicates the ability of energy and matter to disperse into their environmental space. The amount of exergy can be obtained from the energy and entropy balance equations together with the concept of environmental temperature. The necessity of exergy concept comes from the fact that so-called “energy” issues are in fact to be called “eXergy” issues, since the concept of exergy does articulate what is consumed. This applies to all of heat and mass transfer occurring within the human body as a living thermodynamic system as well (Shukuya, 2013).

Exergy analysis of the built environment equipped with space heating and cooling systems, whether they are passive-technology based or active-technology based, articulates how much and where exergy is consumed in the whole process from its supply and consumption to the resulting entropy generation and disposal. Exergy research focussing on thermal physiological behaviour of human body has also progressed very much over the last fifteen years or so, but its major focus so far has been on quasi steady-state conditions and much has still to be researched in particular on unsteady-state conditions and also their relation to thermal perception (Shukuya, 2009, 2013; Schweiker et al., 2016).

3. Exposure to varying thermal conditions indoors and outdoors

Figure 1 outlines a two-stage subjective experiment performed in order to clarify the above-mentioned feature (Nagai et al., 2014). As the 1st stage, thiry-eight persons at the age from 20 to 21 years old were asked to carry a set of compact sensors for measuring grey-colored globe temperature, air temperature, and relative humidity as shown in the bottom left of Figure 1. The purpose of this measurement is to know their overall themal environmental conditions for respective one-week periods.

Figure 2 shows two examples of the variation of measured globe temperature values in the vicinities of two persons, S and W, whose average values of globe temperature were the highest at 29.6ºC and the lowest at 25.1ºC among 38 persons, respectively. We can see that the globe temperature varies from time to time. The range of globe temperature is from 20 to 36ºC for Subject_W, whose average is the lowest, and from 24 to 38ºC for Subject_S, whose average is the highest. The outdoor air temperature measured at the weather station

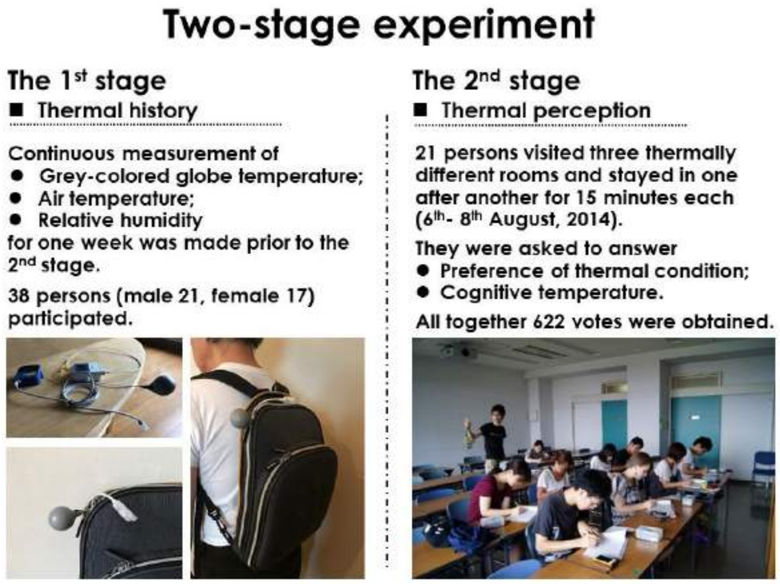


Figure 1. A two-stage experiment to clarify the dynamic nature of thermal perception

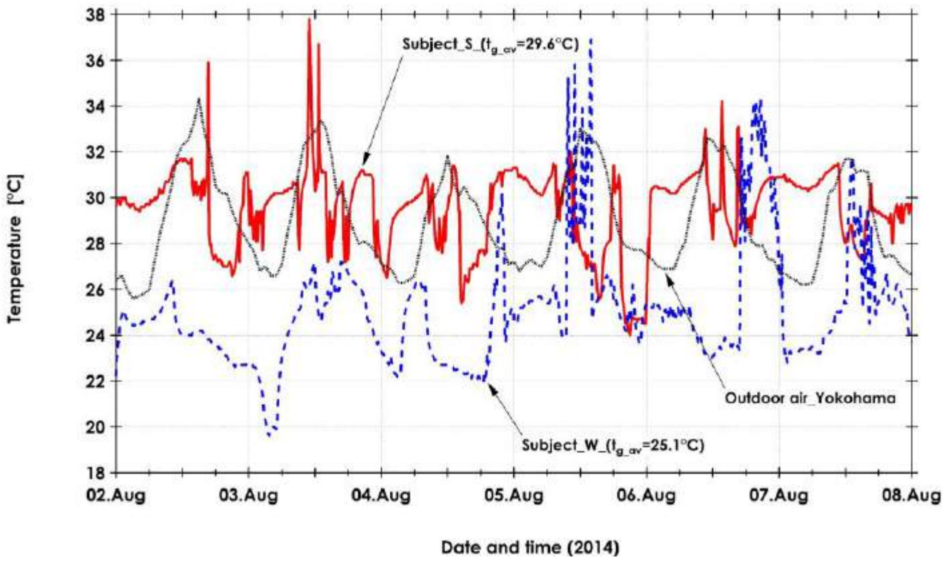


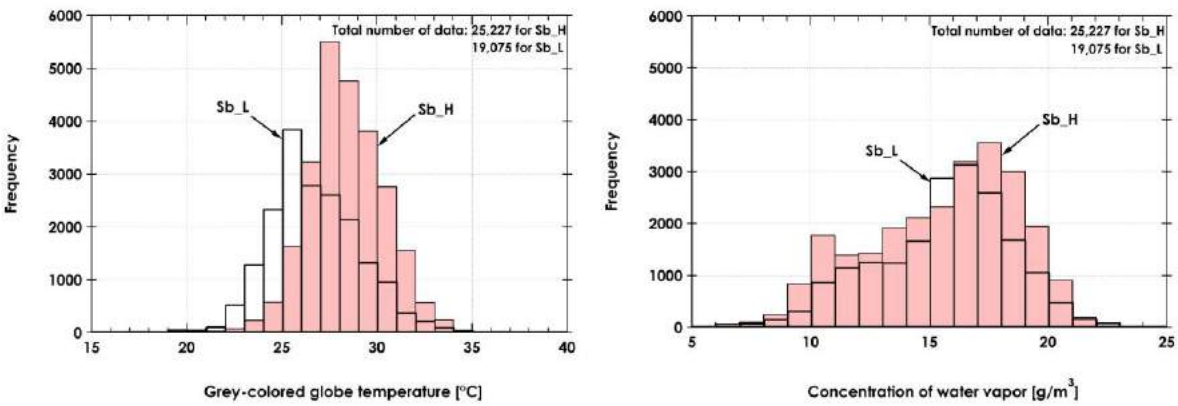
Figure 2. Variation of globe temperature in the vicinities of two subjects for six days together with outdoor air temperature measured at the nearby weather station.

in Yokohama varies diurnally between 26 and 32ºC and the variation looks rather milder than the globe temperature measured in the vicinities of the two persons. These two persons live in geographically the same regions, but as their measured globe temperatures for a one-week period demonstrate, they are as though living in different climatic regions.

All of the 38 subjects were devided into two groups, Sb_H and Sb_L : Sb_H is the group of those 22 subjects being with their average globe temperature higher than the whole average, 27.6ºC, and Sb_L is the group of those 16 subjects being with lower.

Figure 3 shows the frequency distribution of grey-colored globe temperature and water vapor concentration of these two groups of subjects, Sb_H and Sb_L, respectively. There is an obvious difference, 2 K, in the median values of measured globe temperature, t_g; it is at the rank of 27.5ºC ($27 \le t_g < 28$) in the group Sb_H, while on the other hand, at the rank of 25.5ºC ($25 \le t_g < 26$) in the group Sb_L. There is not such a clear difference in the case of water vapour concentration. Therefore, 38 persons were not separated with respect to water-vapour concentration.

All of 38 subjects were invited to the 2nd stage of experiment and 21 out of them could



a) Globe temperature b) Water-vapour concentration

Figure 3. Frequency distribution of globe temperature and water vapour concentration measured in the vicinities of 38 subjects for a one-week period. Sb_H and Sb_L denote two groups of subjects, whose respective averages of globe temperature are higher or lower than the whole average.

participate in it. As was shown in Figure 1, they visited three thermally differenct rooms from one to another and stayed for 15 minutes each. The three rooms are as follows: one with window closed and no mechanical cooling unit operated (denoted as WC), another with natural ventilation by keeping windows opened (NV), and the last with window closed and mechanical cooling unit operated (MC). All together they were exposed to these varying themal environments for the period of two and a half hours, and during the participation they were asked to answer their preference and also cognitive temperature (Saito, 2015).

Answering their preference and cognitive temperature was made four times in each room: firstly right after entering a room; secondly five minutes later; thirdly further five minutes later; and lastly right before leaving the room. The preference asked was whether they prefer lowering the room temperature, prefer keeping it as it is, or prefer raising the room temperature. The cognitive temperature is a single value of temperature that they imagine in accordance with their experiencing conditions. It is considered to reflect not only the present state of thermal conditions that the subjects are experiencing but also their respective thermal history that they had unconsciously built up until then as demonstrated in Figure 2. This 2nd stage experiment was performed for three days, from 6th to 8th of August, 2014 and altogether 622 votes were obtained.

Figure 4 demonstrates the variation of thermal environmetal condition for the participants indoors together with the outdoor environmental conditions during the series of visit from WC to NV, WC to MC, and so forth on 6th August, 2014. It was a typical hot and humid summer day in Yokohama area. Other two days, 7th and 8th August, were more or less the same as the first day. For one session of the experiment, six, seven or eight subjects participated in and they made visit in the course of WC → NV → WC → MC → and so on as indicated in the graphs.

In WC, the MRT and room air temperature were almost the same as each other and they are 2 to 3 K lower than outdoor air temperature. In NV, the MRT was slightly higher than room air temperature when the first visit was made, but they were almost the same as each other when the second visit was made. Room air temperature and the MRT in NV was the highest in three rooms, since the outdoor air, whose temperature is higher than the room air temperature in WC, was taken in by natural ventilation.

In WC, no window was opened and no mechanical cooling was on so that the air velocity was the lowest in three rooms, while in NV the air velocity fluctuated in the range from 0.4 to 0.9 m/s because of the windows being kept open. In MC, the air velocity was observed slightly higher than that in WC and the room air temperature was the lowest in three rooms. It was about 27ºC, which is approximately 5 to 6ºC lower than outdoor air temperature and 2 to 3ºC lower than the room air temperature in WC. Throughout all sessions, relative humidity indoors and outdoors are more or less in the range between 50 to 57%. In room MC, the relative humidity is the lowest at about 50%. As shown in the middle graph, ET* calculated using the set of measured data is the highest in NV, the lowest in MC and in between in WC.

The bottom graph shows the variation of human-body exergy consumption rate calculated using the measured data mentioned above. Since the measurement was made at one-minute intervals, the human-body exergy balance calculation was also made at one-minute intervals. For this calculation, the metabolic energy generation rate and the clothing insulation were assumed to be 1.1 Met and 0.3 clo. The first twenty-minute period in Figure 4 is the period for preliminary calculation so that the actual results to be seen are from 10:30 on.

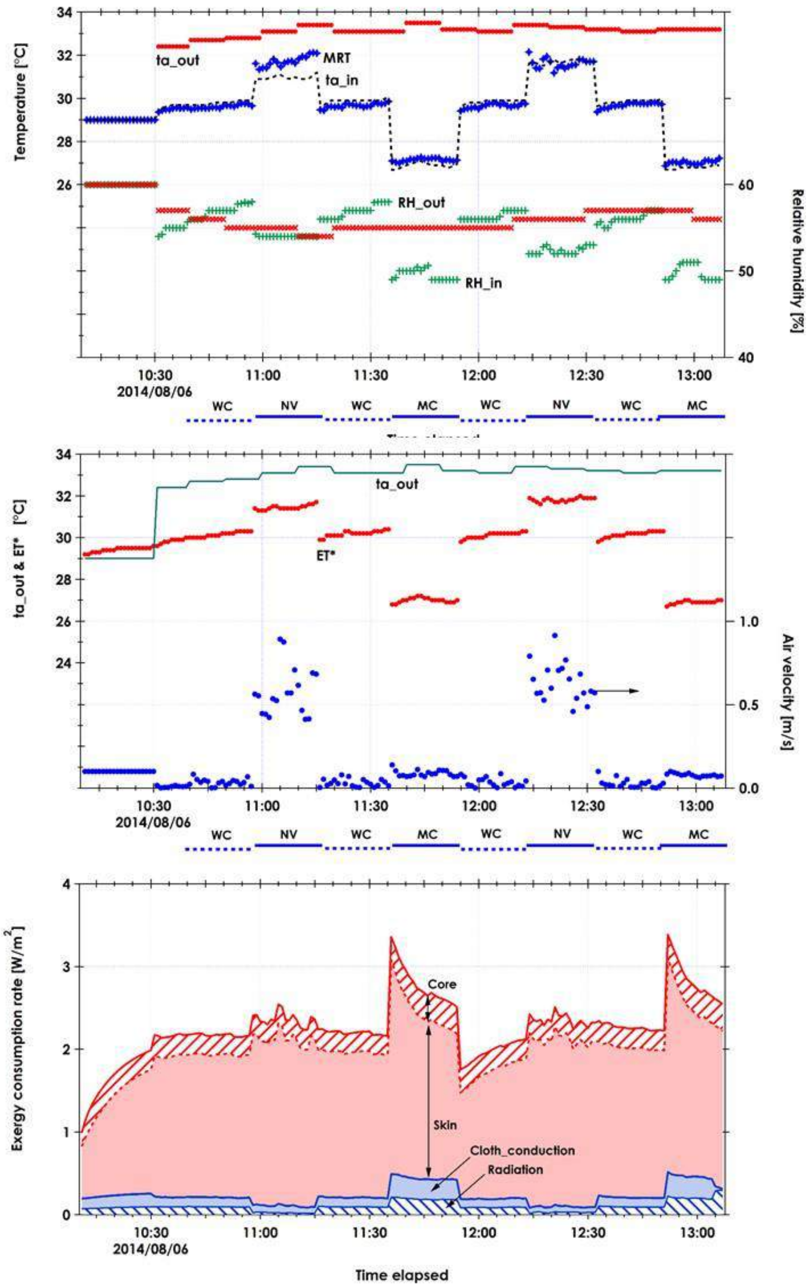


Figure 4. Variation of thermal environmental condition in one session of the 2nd stage experiment and variation of the human-body exergy consumption rate calculated

The human-body exergy consumption rate varies from time to time depending on the thermal conditions of three rooms. A sharp rise of HBXC rate emerges right after they enter room MC from room WC. On the other hand, a sharp drop of HBXC rate emerges right after they enter room WC from room MC. In room NV, the whole HBXC rate varies in response to the fluctuation of air velocity. The attenuating feature appeared in the variation of HBXC rate is exactly the reflection of unsteady-state calculation.

Since this is a summer case, the exergy consumption emerged at the skin layer occupies the largest portion within the whole HBXC rate. This is particularly so in room NV, since the exergy consumption due to the conduction between the skin layer and the clothing ensemble and also the exergy consumption due to the absorption of radiation becomes the smallest for the MRT and air temperature being the highest. In room MC, the exergy consumption due to conduction and absorption of radiation becomes large for the lowest values of the MRT and room air temperature. These features together with the low relative humidity about 50% makes the whole HBXC rate in room MC be the largest.

All of the 622 preference votes obtained from the participants in the 2nd stage experiment held for three days were allotted in the bins of HBXC rate such as $1.0 \le X_C < 1.1$, $1.1 \le X_C < 1.2$, $\cdots$, and so on, where X_C denotes the whole HBXC rate [W/m^2], and then, the percentage of subjects who prefer lowering the room temperature in each bin was calculated. This calculation was made for all participants together and also for two groups of the participants, Sb_H and Sb_L, separately. Figure 5 shows the results in the case of all participants, since there was no significant difference for Sb_H and Sb_L. As can been seen, the smaller the HBXC rate, the more prefer lowering the room temperature. The percentage of people prefering to lower the room temperature, p_L [%], can be expressed by the following logistic curve as a function of HBXC rate, X_C, with the coefficient of determination being 0.724 and the level of significance being less than 1% .

$$p_L = \left(\frac{1}{1 + e^{3.940 X_c - 7.399}} \right) \times 100 . \tag{1}$$

For the condition, at which the HBXC rate becomes 1.5 W/m^2, approximately 80% of subjects prefer lowering the room temperature. On the other hand, for the conditions, at which the HBXC rate is 2.2 W/m^2, approximately 20% of the subjects prefer lowing the room temperature. It implies that 80 % of the subjects would not need a change of thermal condition. With this statistical evidence in mind, let us again take a look at the bottom graph of Figure 4. We find that the HBXC rate ranging from 2.2 to 2.5 W/m^2 is realized in room NV.

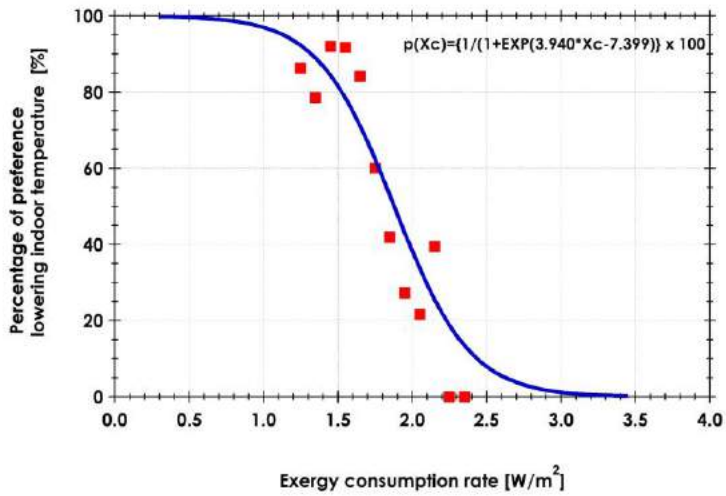
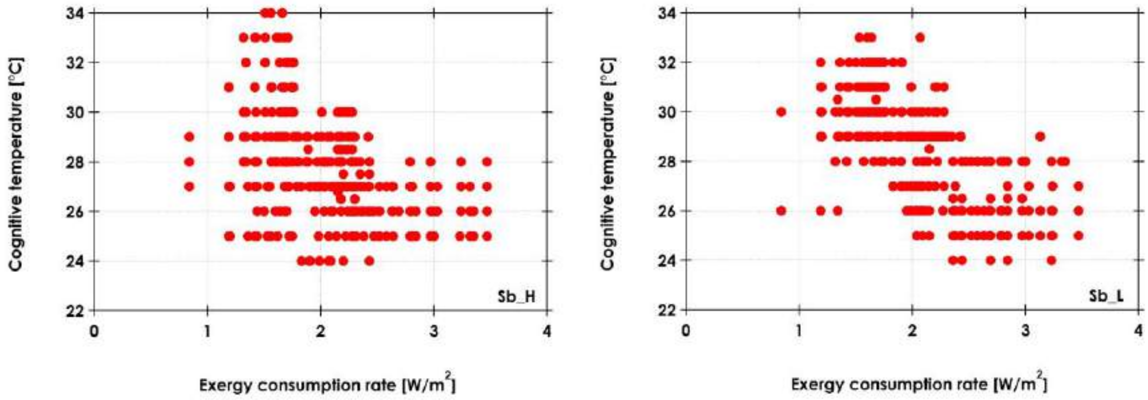


Figure 5. The relationship between HBXC rate and the percentage of subjects who prefer lowering the room temperature

4. Radiant exergy input rate and avoidance of discomfort

Since, as described earlier, the cognitive temperature as the other subjective appraisal of thermal condition was asked in addition to the preference, whether or how it relates to HBXC rate was examined as shown in Figure 6. The examination was made for Sb_H and Sb_L separately. Since the cognitive temperature is a kind of subjective indicators, the plots scatter much against a certain value of HBXC rate, but there look some patterns as a whole. As the



a) Sb_H b) Sb_L

Figure 6. Cognitive temperature and its relation to HBXC rate

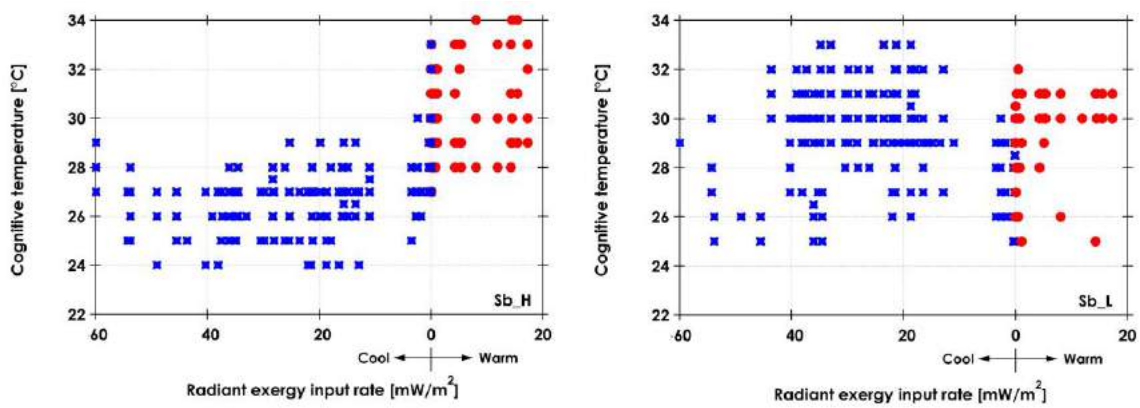
two graphs show, the smaller is the HBXC rate, the higher is the cognitive temperature. This tendency looks similar to each other for both Sb_H and Sb_L and it is consistent with what can be seen in Figure 5.

The same way of comparison was also made with respect to radiant exergy input rate, radiant exergy emission rate, and outgoing exergy rate by convection, and it was found that there is hardly any correlation at all between the cognitive temperatue and radiant exergy emission rate and also between the cognitive temperature and outgoing exergy rate by convection. But, there was some distinctive pattern suggesting a correlation between the cognitive temperature and the radiant exergy input rate for Sb_H, but not for Sb_L as shown in Figure 7. Thermal radiant exergy input rate used here in Figure 7 were calculated from the following equation (Shukuya, 2013).

$$x_r = \varepsilon\sigma\left\{\left(T^4 - T_o^4\right) - \frac{4}{3}T_o\left(T^3 - T_o^3\right)\right\} \approx \varepsilon h_{rb} \frac{\left(T - T_o\right)^2}{\left(T + T_o\right)}, \quad (2)$$

where ε is the overall emittance of the surface, which is usually higher than 0.9 in the case of building envelopes; σ is Stephan-Boltzmann constant (=5.67x10^{-8}) [W/(m^{2}K^4)]; and T and T_o the surface temperature and environmental temperature in Kelvin, and h_{rb} the radiative heat transfer coefficient of black-body surface, which is 5.5 to 6 W/(m^{2}K).

Figure 8 demonstrates a numerical example of radiant exergy emission rate of a unit-area surface as a function of surface temperature. There is no radiant exergy flow from a surface whose temperature is the same as the environmental temperature T_o As the surface



a) Sb_H b) Sb_L

Figure 7. Cognitive temperature and its relation to radiant exergy input rate

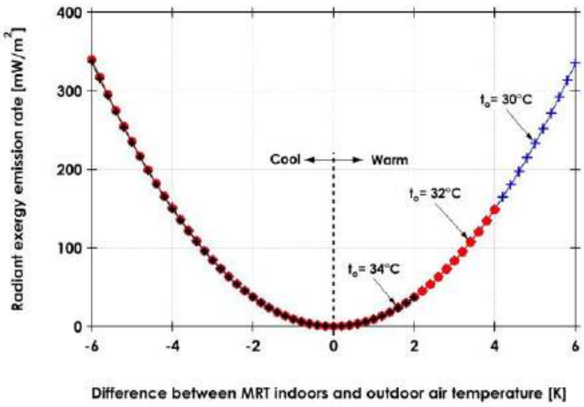


Figure 8. Radiant exergy as a function of surface temperature. A surface, whose temperature is higher than the environmental temperature, emits "warm" radiant exergy and lower emits "cool" radiant exergy.

temperature goes higher than the environmental temperature, the radiant exergy emission rate becomes larger. The same is true as the surface temperature goes lower. The former is called "warm" radiant exergy and the latter "cool" radiant exergy. It is noteworthy that the radiant exergy emission rate ranges from 0 to 100mW/m^2 in typical summer condition of built environmental spaces that we usually reside.

Coming back to Figure 7, for Sb_H, whether "cool" or "warm" radiant exergy is available looks affecting the values of cognitive temperature, while on the other hand, for Sb_L, it does not look so. Since the thermo-sensory portals of human body is embedded within the outermost portion of skin layer, radiant exergy input, whether it is "warm" or "cool", could be the primary stimulant to the brain, which functions the perception and the follow-up consciousness to emerge. Assuming it to be so, Sb_H is sufficiently sensitive to the availability of radiant exergy, but Sb_L is not.

According to a previous investigation on the role of radiant exergy emission rate from the surrounding surfaces in naturally ventilated rooms (Tokunaga et al., 2005; Shukuya et al., 2006; Shukuya, 2013), the avoidability of discomfort is very much influenced by the availability of "warm" or "cool" radiant exergy. This result is depicted in Figure 9 as the preference lowering the indoor temperature; the circular plots represent the experimental result given by Tokunaga et al. (2005) and the curve represents their logistic regression. Shown together is the perecentage of Sb_H and Sb_L, who prefer lowering the room temperature, given in the present investigation. Since the number of votes obtained were much smaller than in the previous studies done by Tokunaga et al., the size of bins for radiant exergy emission rate were made larger: e.g. from 0 to 20 mW/m^2, 20 to 40 W/m^2 and so on.

In the thermal condition, in which "warm" radiant exergy available, it is very likely that the preference lowering the room temperature emerge regardless of either Sb_H or Sb_L. But in the thermal condition, in which "cool" radiant exergy is available, the emergence of preference look rather different, depending on whether one belongs to Sb_H or Sb_L. The subjects of Sb_H look very responsive to the turnover of radiant exergy from "warm" to "cool", but those of Sb_L look less responsive. This is considered due to the subjects of Sb_L having been exposed very often to the thermal environmental condition with low temperature. They cannot be responsive to the condition of MRT being 1 or 2 K lower than outdoor air temperature. On the contrary, those belonging to Sb_H are rather highly sensitive to the change in MRT, as was indicated by the cognitive temperature given by them as shown in Figure 7.

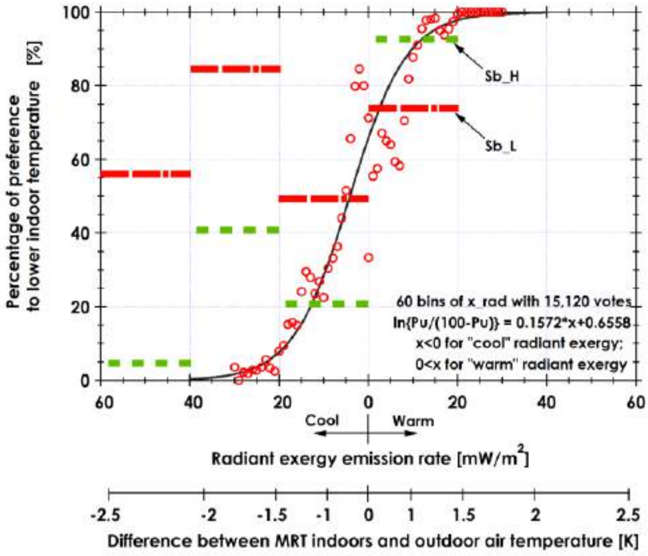


Figure 9. The relationship between radiant exergy emission rate from the surrounding surfaces and the percentage of subjects who prefer lowering the room temperature

5. Conclusions

In order to have a better understanding of ever-changing environmental conditions and its relation to human-body exergetic behaviour together with thermal perception for hot and humid summer cases in particular, a two-stage experiment was performed. What has been found so far in this series of investigation is as follows:

1) The participants of the experiment were always exposed to a variety of indoor and outdoor thermal conditions;
2) The smaller is the human-body exergy consumption rate, the more the percentage of people who prefer lowering the room temperature;
3) Whether "cool" or "warm" radiant exergy is available influences very much on the thermal preference;
4) It is particularly so for those whose surrounding thermal conditions tend to be with higher temperature than those with lower.

6. References

Nagai R. et al. 2016. Research on the effect of long-term thermal history on thermal perception and human-body exergy balance. Proceedings of Annual Meeting of Architectural Inst. of Japan. 309-310.

Saito M and Tsujihara M. 2015. Thermal adaptation of elementary students in summer based on cognitive temperature scale in the case of Sapporo and Kumamoto. Proceedings of Annual Meeting of Architectural Inst. of Japan. 471-474.

Schweiker M. et al. 2016. Unsteady-state human-body exergy consumption rate and its relation to subjective assessment of dynamic thermal environments. Energy and Buildings. 116: 164-180

Shukuya M. et al. 2006. Thermal radiant exergy in naturally-ventilated room space and its role on thermal comfort. Proceedings of Healthy Buildings 2006 Vol. IV. 257-262.

Shukuya M. 2009. Exergy Concept and Its Application to the Built Environment. Building and Environment. 44(7): 1545-1550.

Shukuya M. 2013. Exergy – Theory and applications in the built environment. Springer-Verlag London.

Tokunaga K. et al. 2005. An experimental study on thermal comfort caused by solar-heat control and ventilation in summer season – the relationship between radiant environment and comfort. Proceedings of Annual Meeting of Architectural Inst. of Japan. 607-608.

PAPERS NOT PRESENTED

PAPERS appearing in the proceedings but authors unable to present

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Thermal comfort and heat stress in cross-laminated timber (CLT) school buildings during occupied and unoccupied periods in summer

Timothy O. Adekunle[1]

[1] Department of Architecture, College of Engineering, Technology, and Architecture (CETA), University of Hartford, 200 Bloomfield Avenue, West Hartford, CT 06117, USA.
Correspondence email: adekunle@hartford.edu

Abstract: This study investigates thermal comfort and heat stress in CLT school buildings during occupied and unoccupied periods in summer by evaluating Wet Bulb Globe Temperature Heat (WBGT) index and Universal Thermal Climate Index (UTCI). As structural timber is increasingly used for the construction of various buildings and such buildings are susceptible to summertime overheating as discussed in existing studies, the study aims to understand the heat stress index and temperatures at which the vulnerable occupants will be subject to heat stress in CLT school buildings. The case study is an educational building located in the Northeast region, USA. The survey was conducted from June-August 2017. The environmental parameters (temperature, RH, dew-point temperature-DPT) were measured at 15-minute intervals but measurements taken at every 60 minutes were considered in this study. The WBGT and UTCI were also calculated for comparison. The external temperature was collected from a nearby weather station. The building was occupied from 08:00-17:00 and unoccupied from 18:00-07:00. The results showed the average temperature in the main hall on the lower floor (a double-volume space) was 21.2°C. The average temperature in the classroom on the upper floor level was 24.1°C. The average WBGT varied from 18.8-20.0°C while the average UTCI varied from 21.9-24.0°C. The findings showed the vulnerability of the occupants to summertime temperatures in the spaces on the upper floor especially when the building is naturally ventilated. Applying the WBGT index and UTCI heat index to determine the heat stress thresholds, the study recommends the WBGT of 19.3°C (occupied) and 20.0°C (unoccupied); the UTCI of 23.4°C and 24.0°C for occupied and unoccupied periods respectively. Overall, the study highlights WBGT of 19.8°C and UTCI of 23.9°C as possible heat stress indicators for the vulnerable occupants in CLT school buildings. The investigation revealed a higher UTCI heat stress index than the WBGT index for occupants because higher wind speeds at warm temperatures do not have a significant impact on WBGT.

Keywords: Thermal comfort, heat stress, Wet Bulb Globe Temperature Heat (WBGT) index, Universal Thermal Climate Index (UTCI), CLT school buildings, occupied and unoccupied periods

1. Introduction

Existing research has highlighted that structural timber products such as cross-laminated timber (CLT) are increasingly used for the construction of different buildings (Adekunle, 2014); and such buildings are prone to elevated temperatures and summertime overheating (Adekunle and Nikolopoulou, 2014, 2016). The study intends to understand the heat stress index and temperatures at which the vulnerable occupants will be subject to heat stress in CLT school buildings. Investigations on thermal comfort of occupants in school buildings have been extensively considered in different parts of the world (Rupp et al., 2015). Existing studies in the field have been focusing on the thermal comfort of people including different age groups in school buildings (Corgnati et al., 2007; Hussein and Rahman, 2009; Mors et al., 2011; Teli et al., 2013). Thermal comfort of occupants has been investigated in naturally ventilated school buildings in hot, humid climate (Hussein and Rahman, 2009). The study highlighted that 80% of the survey participants accepted the thermal environment (Hussein and Rahman, 2009); while the votes reported on the actual thermal sensation are more than the threshold recommended by ASHRAE 55 (ASHRAE, 2013). The study carried out by Hussein and Rahman (2009) revealed that occupants of the school buildings in hot, humid climate tend to adapt to the heat within the thermal environment. Also, the applicability of the adaptive thermal comfort model in school buildings with natural ventilation has been studied (Hwang et al., 2009). The findings of the study conducted by Hwang et al., (2009) showed the acceptability rate has a broader range while the comfort zone has a smaller band when compared to the adaptive thermal comfort model.

In the Netherlands, a study considered various environmental variables in different seasons and found out the respondents tend to prefer temperatures at a lower rate within the thermal environment (Mors et al., 2011). In the western part of Europe (England), the applicability of the adaptive comfort model in naturally ventilated school buildings has been studied (Teli et al., 2012). The comfort temperature was 2.0°C lower than the comfort temperature calculated from the adaptive comfort model (Teli et al., 2013). The study (Teli et al., 2013) revealed the occupants are more susceptible to elevated temperatures in school buildings. In another study conducted on school buildings in Italy, the results revealed the occupants found the thermal environment acceptable even when they feel 'no change' or 'warm' (Corgnati et al., 2007). An investigation conducted at the end of the summertime in Southampton, UK highlighted the respondents were found to be tolerant to elevated temperatures and indicated their preference for the warm part of the scale (thermal sensation). While the occupants did not indicate a strong preference for the thermal environment to be much cooler (Teli et al., 2014). In a Mediterranean climate, a study carried out in school buildings showed the acceptable temperature for the occupants exceeded the comfort zone (Pereira et al., 2014). However, no investigations were conducted on the heat stress index for occupants in school buildings.

Montazami and Nicol (2013) conducted a study in different school buildings in the UK and proposed that further developments are required in addition to the newly introduced overheating guidelines designed for schools in the country. A study carried out in Taiwan by Liang et al., (2012) highlighted that the building envelope energy regulation has a significant effect on the occupants' comfort in school buildings. Also, a relationship is found between indoor air quality and energy efficiency of buildings (Katafygiotou and Serghides, 2014). Relative humidity is found to have a less significant impact on occupants' sensation in school buildings (Hwang et al., 2006). Also, the occupants in school buildings in a hot, humid region are more tolerant to heat and relative humidity when they are compared to the occupants in school buildings in temperate climates (Zhang et al., 2010). The study conducted by Zhang et al., (2010) suggested that occupants of school buildings located in the temperate region may be at risk to heat and elevated temperatures since they are less tolerant to heat and humidity. Therefore, further research on the heat risk needs to be considered at various periods in school buildings.

Zhang et al., (2013) also stated that occupants in non-naturally ventilated spaces in buildings tend to ensure the thermal environments are more comfortable than naturally ventilated spaces. The occupants also tend to consider the adaptive measures at an early stage to adjust the thermal environment. The study by Zhang et al., (2013) maintained that the occupants in non-naturally ventilated buildings tend to be sensitive and perceive the thermal environment much better than the occupants in naturally ventilated buildings. A study identified excessive use of both heating and cooling systems with low temperatures in the summertime and extremely high temperatures in wintertime in school buildings (Serghides et al., 2014). In another field survey, the investigation revealed the occupants of the buildings are not thermally comfortable, and the responses from the occupants revealed the heating, ventilation and air-conditioning system needs to be replaced (Yau, 2008). As reported in a study carried out by the National Institute for Occupational Safety and Health on indoor environmental quality, temperature and relative humidity measurements are taken to understand the parameters that influence the perception of comfort within the thermal environment (NIOSH, 2015). The study stated further that the perception of comfort is closely related to physiological adjustments, the heat transfer from the body to the environment, as well as body temperature. The study highlighted the heat transfer from the body to the thermal environment is determined by temperature, humidity, movement of air, personal activities and clothing insulation. ASHRAE 55 also specifies the operative temperature could range between 19.5°C (67°F) and 27.8°C (82°F). The standard 55 states that the comfort temperatures threshold within the thermal environment depending on relative humidity, seasonal change, level of activity, clothing worn by people and other parameters (ASHRAE, 2013). While relative humidity between 30% and 60% is recommended within the indoor environments to avoid or minimize the growth of mold (EPA, 2012). Also, ASHRAE 62.1 recommends relative humidity not more than 65% within the indoor environment to avoid microbial growth (ASHRAE 62.1, 2013).

Regarding occupied and unoccupied settings in buildings, it is expected that buildings with HVAC systems usually put off the systems during the unoccupied period (that is, night time or when the buildings are not occupied) while the ventilation systems are operated during the occupied period. The change between occupied and unoccupied settings in buildings is a way to reduce energy consumption during unoccupied period. In most cases depending on the external conditions, the energy consumption is not usually reduced when the systems are not operated as it takes more energy to keep the thermal environment within the comfortable range when the systems are operated (NIOSH, 2015). The study mentioned that the set-point temperatures could be indicated using thermostats in buildings with new HVAC systems in preparation for occupation. However, temperature and humidity need to be always maintained to meet the recommended thresholds specified by ASHRAE 55 (ASHRAE 55, 2013) and ASHRAE 62.1 (ASHRAE 62.1, 2013) primarily when people occupy the buildings. As a result, excessive heat or elevated temperatures during the unoccupied period in buildings may probably affect the thermal comfort of occupants and their level of productivity especially during the first few hours of occupation.

Existing research has highlighted that in general, buildings are expected to provide a comfortable thermal environment for occupants during periods of high summertime temperatures, particularly during the period of heat waves (NHS, 2011). In most cases, elevated temperatures in summertime are of great concern to vulnerable occupants especially in naturally ventilated in buildings (Lomas and Giridharan, 2012). To ensure the thermal comfort of occupants during the summer season, air-conditioning systems are provided and installed to achieve occupants' comfort and such buildings are not energy-efficient and sometimes expensive to maintain (DOE, 2015). Even when the buildings are expected to be free-running in the summertime, the heating systems usually come on when the external temperature drops. Sometimes the cooling systems will turn on when the external temperatures rise due to the installation of thermostats in the buildings (Nicol and Humphreys, 2007; Nguyen et al., 2014). Based on these developments, thermal comfort of occupants and the performance of offices and classrooms are evaluated in CLT school buildings using the CIBSE thermal comfort model (CIBSE, 2015) and the adaptive thermal comfort model (BSEN15251, 2008). As discussed in existing research that the BSEN15251

(BSEN15251, 2008) applies to free-running buildings (that is, naturally ventilated buildings that are supplemented with the use of fans with no air-conditioning). Since the case study building is naturally ventilated in the summer and augmented with the cooling systems such as fans and mechanical ventilation system, the thermal performance can be assessed using the CIBSE thermal comfort model (CIBSE, 2015) and the adaptive thermal comfort model (BSEN15251, 2008).

The literature provided a throughout account of the state-of-the-art on thermal comfort in school buildings with no documentation of occupants' comfort and heat stress in CLT school buildings. Therefore, the research investigates thermal comfort of occupants and heat stress in cross-laminated timber (CLT) school buildings during occupied and unoccupied periods in summer by evaluating Wet Bulb Globe Temperature Heat (WBGT) index and Universal Thermal Climate Index (UTCI) for comparison. The study also considered the two heat indexes to understand the extreme heat index in the school buildings. The findings on thermal comfort of occupants in the buildings are compared to the existing studies in the field to understand if the comfort temperatures exceed the adaptive comfort thresholds. A study on the applicability of the PMV model as recommended by CIBSE Guide A 2015, 1.5.3 will be considered in future research.

2. Research approach and mathematical models

The applicability and limits of various standards (such as the CIBSE and the BSEN15251 thermal comfort models) used for evaluation of the performance of spaces and the summary of the standards have been presented in existing research (Adekunle and Nikolopoulou, 2014, 2016; Giridharan, 2017). The features of the thermal comfort standards (CIBSE, 2015; BSEN15251, 2008) applicable to this study are summarized in the table below (Table 1).

Table 1. Parameters for evaluation of the indoor temperatures in the spaces and buildings

Metrics for evaluation	**Thermal comfort standard**	**Thresholds for the standard**	**Spaces/buildings that can be evaluated using the standard**	**Additional notes on the standard**
Number of hours above 25°C and 28°C during the occupied period (08:00-17:00).	CIBSE (2015)	The number of hours above the thresholds not above 5% of the 25°C and 1% of the 28°C during the occupied period.	Offices and classrooms including other useable spaces such as assembly hall, staff lounge, and laboratories.	In general, the values apply to usable spaces in buildings.
Number of hours above 24°C and 26°C during the unoccupied period (18:00-07:00).		The number of hours above the thresholds not more than 5% of the 24°C and 1% of the 26°C during the unoccupied period.	Offices and classrooms including other useable spaces such as rest area, nurse station, first aid.	
The BSEN15251 (adaptive) thermal comfort for Category I thermal envelope including the running mean temperature.	BSEN15251 (2008)	The number of hours not more than 5% of the total hours above the Category I thermal envelope.	Spaces/buildings that are occupied by vulnerable occupants such as young people, sick and disabled, pregnant women etc with 'high level of expectations'. The spaces include rest area, nurse station,	The BSEN15251 standard applies to free-running spaces/buildings (that is, spaces with manually operated windows and mechanical ventilation but

			first aid, classrooms, and offices.	no air-conditioning systems).
The BSEN15251 thermal comfort for Category II thermal envelope including the running mean temperature.		The number of hours not more than 5% of the total hours above the Category II thermal envelope.	Spaces/buildings that are occupied by occupants with 'normal level of expectations'. The spaces include classrooms, offices, and laboratories.	

The thermal comfort standard (CIBSE, 2015) also explains the building category used for calculating maximum acceptable temperature (T_{max}). Also, the CIBSE thermal comfort standard suggests that every designer should aim to remain within the Category II (suggested acceptable range is 3K) thresholds. For CIBSE TM52, it is recommended that the Category II upper limit should be applied using Equation 1. The equation (Equation 1) explains the maximum acceptable temperature Category II TM52; while T_{rm} is the running mean temperature.

$$T_{max} = 0.33\, T_{rm} + 21.8 \qquad \text{Equation 1}$$

For the field investigation, the measurements of environmental parameters (temperature, dew-point temperature, and relative humidity) were taken at every 15 minutes using sensors at 1.1 m height above the floor level in line with ASHRAE 55 (ASHRAE, 2013). However, the measurements taken at every 60 minutes were considered for this study. The Wet Bulb Globe Temperature Heat (WBGT) index and the Universal Thermal Climate Index (UTCI) were also calculated. All the spaces monitored have windows that can be manually operated. The windows were being used for ventilation during the field study, and mechanical ventilation system was operated when the indoor temperatures increase. The US military formulated the WBGT heat stress index, but the heat index has been considered lately for evaluation of heat stress in other functional spaces such as offices and workspaces (NEHC, 2007; OSHA, 2016). The details of the WBGT heat index has been considered in the existing research (Stull, 2011; Lemke and Kjellstrom, 2012). While the UTCI heat stress index was developed by the COST Action 730 under the sponsorship of the European Union (EU); the sole aim of evaluating the thermal environment in the principal areas of human biometeorology (Brode et al., 2010). The evaluation of the UTCI heat index should focus on the physiological response of the human body, and it is expected to be simulated by the thermos-physiological model considered as a state-of-the-art model. The details account of the UTCI heat index, and its developmental background has been presented in the past study (Brode et al., 2010). The features and guides to identify heat stress using the WBGT and the UTCI heat stress indexes are provided in table 2 below (Lemke and Kjellstrom, 2012; www.utci.org).

Table 2. Features of heat stress indexes and categories of stress for the WBGT and the UTCI.

The WBGT heat stress index	**Category of stress**	**The UTCI heat stress index**	**Category of stress**
Temperature below 28.6°C	Not more than 60 mins/hour	Temperature below -40°C	Extreme cold stress
			Very strong cold stress
Temperature at 29.3°C	Not more than 45 mins/hour	Temperature at -27°C	
			Strong cold stress
Temperature at 30.6°C	Not more than 30 mins/hour	Temperature at -13°C	
			Moderate cold stress
Temperature at 31.8°C	Not more than 15 mins/hour	Temperature at 0°C	
			Slight cold stress
Temperature above 38°C	Not more than 0 min/hour	Temperature at 9°C	
			No heat stress
		Temperature at 26°C	
			Moderate heat stress
		Temperature at 32°C	
			Strong heat stress
		Temperature at 38°C	
			Very strong heat stress
		Temperature above 46°C	
			Extreme heat stress

About the internal WBGT (represented as $WGBT_{ind}$°C), it is defined as the combination of natural wet bulb temperature (T_{nwb}°C) as well as black globe temperature (T_g°C) shown in Equation 2 (Lemke and Kjellstrom, 2012). During the field investigation in most cases, it may be time-consuming and laborious to measure the globe temperature within the indoor spaces. As a result, a simplified equation developed by Bernard and Pourmoghani (1999) has been validated by existing research (Lemke and Kjellstrom, 2012). The simplified equation (Equation 3) for heat stress index highlights that occupants are not vulnerable to the thermal environment and the equation is used to evaluate the thermal environment by considering psychrometric wet bulb temperature (T_{pwp}°C), dry bulb temperature (T_a°C) as well as air velocity (Vm/s). For the Equation 3, the internal air temperature is expected to be the same as the internal radiant temperature. As widely reported that the internal temperatures recorded in the thermal environment with a low air velocity are regarded as the internal operative temperatures and not internal air temperature. Since the internal operative temperature is a function of air temperature and radiant temperature, measurements taken in the thermal environment with a low air velocity will be affected by other parameters such as the radiant factor.

$$WBGT_{ind} = 0.7T_{nwb} + 0.3T_g \quad \text{Equation 2}$$

$$WBGT = 0.67T_{pwp} + 0.33T_a - 0.048\log_{10}V\,(T_a - T_{pwp}) \quad \text{Equation 3}$$

Also, Giridharan (2017) stated that psychrometric wet bulb temperature can be calculated by applying the equation developed by an existing study (Stull, 2011) to show that psychrometric wet bulb temperature (T_{pwp}°C) is the same as the wet bulb temperature - T_w. This is presented in Equation 4. The study conducted by Stull (2011) also showed the applicability of the Equation 4 when T_a is assumed to be 20°C and RH is assumed to be 50% to generate T_w = 13.7°C as shown in Equation 5. The arctangent (atan) function in Equations 4 and 5 considers the values that are similar to values in radians. Equation 4 indicates that T_w is a function of T_a (°C) and RH (%). Equation 4 is also applicable for a pressure of 101.325 kPa or 101325 Pa. The psychrometric standard chart developed by Stull (2011) for a pressure of 101.325 kPa is shown in Figure 1.

$$T_w = T_a \text{atan}[0.151977(RH\% + 8.313659)^{1/2}] + \text{atan}(T_a + RH\%) - \text{atan}(RH\% - 1.676331) + 0.00391838(RH\%)^{3/2}\,\text{atan}(0.023101 \times RH\%) - 4.686035 \quad \text{Equation 4}$$

$$T_w = 20°C\,\text{atan}[0.151977(50 + 8.313659)^{1/2}] + \text{atan}(20°C + 50\%) - \text{atan}(50\% - 1.676331) + 0.00391838(50\%)^{3/2}\,\text{atan}(0.023101 \times 50\%) - 4.686035 = 13.7°C \quad \text{Equation 5}$$

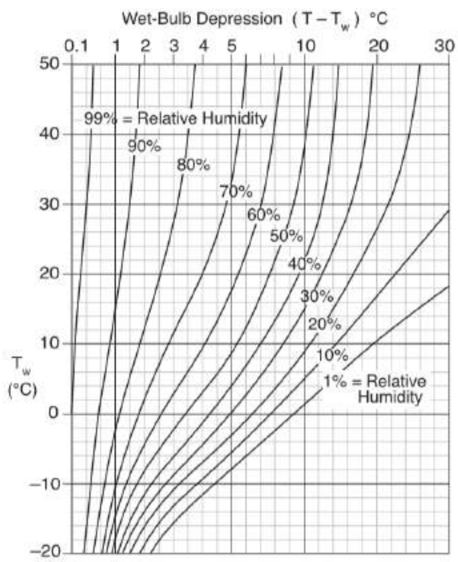


Figure 1. A psychrometric chart for the standard pressure of 101.325 kPa at sea level showing the changes scale for wet-bulb temperature (T_w) and relative humidity (Stull, 2011).

Regarding Equation 3, it has been further validated for an air velocity of up to 3 m/s (Lemke and Kjellstrom, 2012). The equation is developed for workplaces with a threshold of about 31°C for non-vulnerable occupants carrying out various tasks. The threshold of 31°C can be attained by the function of different parameters such as RH and temperature and cannot be considered for evaluation of vulnerable occupants in school buildings. An outdoor temperature at 23°C has been indicated as a threshold for hot weather climate (NEHC, 2007). This revealed the risk of heat stress for vulnerable occupants when the WBGT rises above the threshold which can create health concerns for the vulnerable occupants of indoor environments. As a result, a threshold of 23°C for external temperature will be applied for the WBGT in this study.

For the UTCI heat index, the concept was developed based on the notion of an equal temperature with a reference thermal environment of about 50% RH, high air temperature above 29°C and a vapour pressure not above 2 kPa or 2000 Pa (Blazejckzy et al., 2013). The UTCI is described as the air temperature (T_a) of the reference situation creating the same model effect as actual conditions (Brode et al., 2010; Blazejckzy et al., 2013). While the real values of air influence the deviation of UTCI (also known as the offset) from air temperature and mean radiant temperature (T_{mrt}), wind velocity (V_a) and humidity usually referred to as water vapour pressure (V_p) or relative humidity-RH (Blazejckzy et al., 2013). In the cold season, a wind velocity above 3 m/s will have a more significant effect on UTCI and outdoor temperature above 38°C is critical to the well-being of occupants (Osczevski & Bluestein, 2005); and can lead to very strong heat stress. In general, the UTCI considers the heat exchange between the human body and the immediate environment. Thus, Equation 6 is used to explain the relationship between the human body and the environment in the form of energy balance equation which equals to zero (Blazejckzy et al., 2013). Where M = heat produced by metabolic activity, W = heat produced by muscular activity, C = heat exchange by convection (sensible heat flux), K = Conduction (contact with solids). Also, E = evaporation (latent heat flux), Q = radiation (longwave and shortwave), Res = respiration (latent and sensible), and S = reducing changes in the heat content in the body. Also, a mathematical expression has been developed to explain the UTCI heat index (Equation 7) as highlighted in the existing research (Blazejckzy et al., 2013).

$$M + W + C + K + E + Q + Res \pm S = 0 \qquad \text{Equation 6}$$

$$UTCI = T_a + Offset\ (T_a; T_{mrt}; V_a; V_p) \qquad \text{Equation 7}$$

Advantages of UTCI heat index include its applicability: to the thermo-physiological area across a broader spectrum of heat exchange; to calculations relating to whole-body including local skin cooling. In all climates and seasons from micro to macro scales; as an index for temperature-scale; for various purposes in human biometeorology such as investigations on climate impact as well as public health (Blazejckzy et al., 2013). The equation for calculating the regression function of the UTCI heat index is presented in Equation 8 below (Brode et al., 2010). The equation is developed in line with the human comfort zone to find the coefficient of determination (r^2) between variables. In Equation 8, T_a is air temperature, and T_r is the mean radiant temperature. Also, analysis tools for easy computation of the WBGT and the UTCI heat stress indexes have been developed for broader uses (Climate Chip, 2016). Figure 2 compares the WBGT and the UTCI heat stress indexes.

$$UTCI = 0.995 \times T_a + 0.27 \times (T_r - T_a) \qquad \text{Equation 8}$$

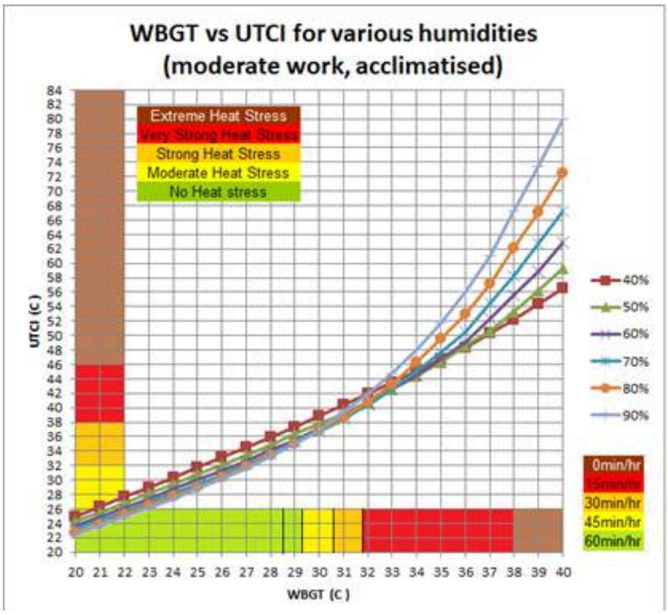


Figure 2. Features and categories of stress for the WBGT and the UTCI heat stress indexes (Climate Chip, 2016)

3. Description of the case study

The case study is an educational building built mainly with cross-laminated timber (CLT) panels. The project is located on an 1800-acre park in the Northeast region, USA. The case study is a mixed-use development comprising of a high school, an urban farm area, and an environmental education centre. The project is considered as one of the first developments in the US to consider CLT as the main structural material. The project has a total floor area of 1300m^2. It consists of office spaces, classrooms, an art studio and a multipurpose hall often used for performance, athletic activities, and community events. The multipurpose hall (double volume) and office spaces are located on the ground floor while classrooms and the artist room are located on the upper floor. For the construction of the case study, the black spruce CLT panels are used for the tension surface and ceiling finishes. Vertical CLT panels are used for bearing and shear walls. The rafters are made of glulam and use to span the multipurpose space on the ground floor. The materials used for the construction of the project include CLT panels, glulam, sheathing, cellulose insulation and dimensional lumber. The project has won many awards and attained LEED-NC 2009 v3 with performance based on 61% energy cost-efficient and over 25% below the ASHRAE Standard 90.1 threshold for schools in terms lighting power density. The U-values of the CLT walls range from approximately 0.13-0.20W/m^{2}K depending on the thickness of the timber panels.

The measurements of parameters were considered in the main office, and the multipurpose hall (on the ground floor – level 1) as well as two classrooms (on the upper floor – level 2). The spaces are naturally ventilated and supplemented with mechanical cooling systems, but the systems are not fully operated during the field investigation. A sensor was installed in each space to measure temperature, relative humidity, and dew-point temperature at the same intervals as earlier stated throughout the field investigation. The survey was conducted from June-August 2017. The external weather data were collected from a nearby meteorological station. The spaces were occupied from 08:00-17:00 and unoccupied from 18:00-07:00. In this paper, the measurements were taken in the selected classrooms (sensors placed in the southwest orientation and north orientation), and the main hall (sensor positioned in the northeast orientation) will be discussed.

4. Data analysis

The average daily external temperature varied from 16.7°C-27.0°C as shown in Figure 3. The mean daily external temperature for the survey period was 22.2°C. The mean maximum and minimum external temperatures recorded were 26.7°C and 17.8°C respectively. The mean daily external dew-point temperature was 17.2°C. The average daily external RH varied from 56%-92% with a mean RH of 73.9%. The average atmospheric pressure at sea level for the period of investigation varied from 1002Pa-1028Pa. The mean WBGT was 19.9°C while the mean UTCI was 23.0°C in the study location. Table 3 summarises the features of the external weather conditions in the study location. The data revealed the summer season was not an extreme summertime in the study location. The analysis showed moderate to strong heat stress index (26.8°C-34.3°C) was found in the study location between June and August. The study showed the heat stress index rise above the 23°C threshold (external) for 24 days during the field investigation.

Table 3. Features of the external weather conditions from June-August 2017 in the study location

Variables	High	Average	Low
Maximum temperature (°C)	32.2°C	26.7°C	17.8°C
Minimum temperature (°C)	22.8°C	17.8°C	12.8°C
Mean temperature (°C)	27.0°C	22.2°C	16.7°C
Dew-point temperature (°C)	24.4°C	17.2°C	7.8°C
Relative humidity (%)	92.0%	73.9%	56.0%
Wind speed (m/s)	9.8m/s	2.2m/s	0m/s
Atmospheric pressure (Pa)	1028Pa	1015Pa	1002Pa
WBGT	25.7°C	19.9°C	13.4°C
UTCI	29.9°C	23.0°C	16.4°C

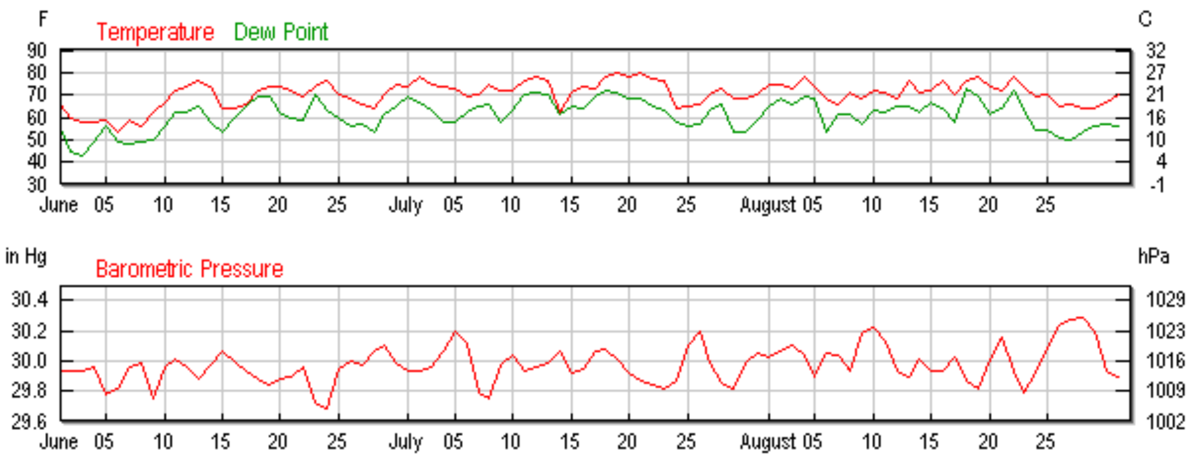


Figure 3. The mean daily external temperature, dew-point temperature (above) and atmospheric pressure (below) in the study location during the field investigation

5. Results and discussions

The results showed the average internal temperature in the main hall (a double-volume space on the ground floor – level 1) was 21.2°C while the mean temperature of 24.1°C was recorded in the classroom on the upper floor during the field investigation. The mean dew-point temperatures of 16.3°C and 13.8°C were measured in the main hall and the classroom respectively. Average RH varied from 52.8% to 73.8% in the main hall and the classroom. Higher temperatures were measured in the classroom than the main hall. The double-volume design of the main hall, floor area, and frequent use of manually operated accessible doors by users may be contributing factors to the lower temperatures recorded in the space. For the occupied, the mean temperature of 23.9°C was noted in the classroom while it was 21.5°C in the main hall. The average temperatures of 20.9°C and 24.2°C were observed in the main hall and the classroom in that order during the unoccupied period. The study showed higher mean temperatures were reported in the classrooms for both periods during the study. On the contrary, higher dew-point temperatures were recorded in the main hall than the classroom for occupied and unoccupied periods. Also, higher RH values are measured in the main hall than the classroom. Table 4 summarises the mean, maximum and minimum values of the variables measured during the field investigation for various periods.

Table 4. Maximum, minimum and mean values of parameters measured in the spaces from June-August 2017

Variables	**Max. temp. (°C)**	**Min. temp. (°C)**	**Mean temp. (°C)**	**Max. dew-point (°C)**	**Min. dew-point (°C)**	**Mean dew-point (°C)**	**Max. RH (%)**	**Min. RH (%)**	**Mean RH (%)**
Main hall (ground floor)	25.8	19.2	21.2	22.1	13.0	16.3	86.1	57.8	73.8
Classroom (upper floor)	29.0	20.7	24.1	20.6	9.3	13.8	72.4	40.8	52.8
Main hall (08:00-17:00)	25.8	19.2	21.5	22.1	13.0	16.5	86.1	57.8	73.1
Classroom (08:00-17:00)	28.9	21.0	23.9	20.5	9.3	12.9	71.4	40.8	50.5
Main hall (18:00-07:00)	25.2	19.2	20.9	19.0	13.0	16.1	83.0	61.1	74.4
Classroom (18:00-07:00)	29.0	20.7	24.2	20.6	9.4	14.4	72.4	42.0	54.5

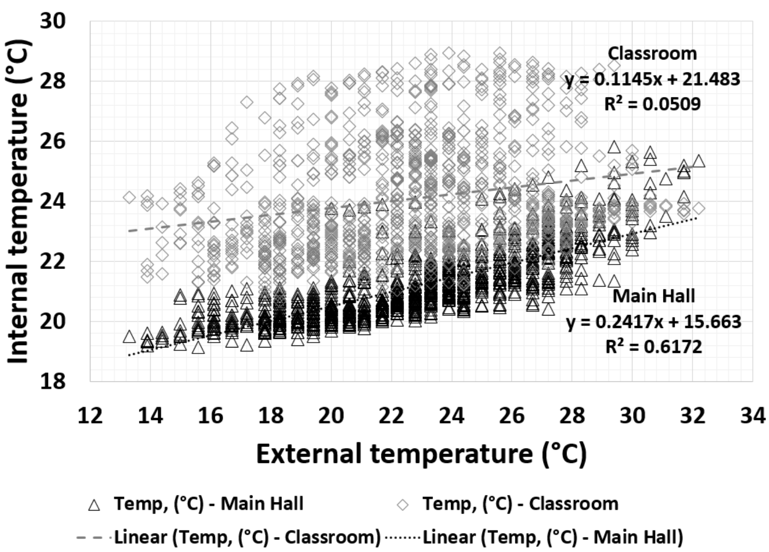


Figure 4. The relationship between the internal and the external temperatures during the field study

Regarding the measured internal temperatures in the spaces and the external temperatures recorded for the study location, a relationship is found between the variables in the main hall (R^2 = 0.6172). However, no relationship is found between the variables in the classrooms (Figure 4). However, higher temperatures are reported in the classrooms than the main hall throughout the field study.

With respect to the WBGT, the values for the spaces were computed by applying Equation 3. For the equation, the air velocity is considered to be 0.1m/s. Also, the UTCI values were calculated using Equation 7 as discussed in the existing study (www.utci.org). The findings showed higher mean the WBGT and UTCI values are calculated in the classroom than the main hall. The study showed the vulnerable occupants are at higher risk of heat stress in the classroom than the main hall. Also, the number of hours above the critical comfort thresholds showed the significant number of hours above the 25°C/28°C and 24°C/26°C in the classroom than the main hall during the occupied and unoccupied periods. The study showed the occupants are prone to summertime overheating. Comparing the WBGT obtained in this study with an existing study on heat stress in hospital spaces (Giridharan, 2017), higher WBGT values were noted in this study than the value reported in the previous study. The values for the WBGT and UTCI are summarised in the table below (Table 5).

Table 5. Comparison of indoor temperatures recorded in the spaces from June-August 2017, with the CIBSE thermal comfort model, WBGT and UTCI heat indexes

Variables	**Mean temp. (°C)**	**Max. WBGT (°C)**	**Min. WBGT (°C)**	**Mean WBGT (°C)**	**Max. UTCI (°C)**	**Min. UTCI (°C)**	**Mean UTCI (°C)**	**No of hours above 25/28°C**	**No of hours above 24/26°C**
Main hall	21.2	23.8	16.7	19.0	27.6	19.4	21.9	7.8/0	27.8/0
Classroom	24.1	24.5	16.6	19.8	29.5	13.2	23.9	301.3/50.3	434.8/179.5
Main hall (08:00-17:00)	21.5	23.8	16.8	19.1	27.6	22.2	19.5	6.5/0	NA
Classroom (08:00-17:00)	23.9	24.5	16.8	19.3	29.5	20.4	23.4	104.8/18	NA
Main hall (18:00-07:00)	20.9	22.4	16.6	18.8	26.1	19.4	21.6	NA	8/0
Classroom (18:00-07:00)	24.2	20.9	16.6	20.0	24.0	20.2	24.0	NA	278.5/115.8

Since the higher WBGT and UTCI values were calculated in the classroom than the main hall, further analysis was considered to find the relationship between the heat indexes (WBGT and UTCI) and the measured variables (temperature and RH). The results showed relationships exist between the variables. A strong correlation is found between the UTCI heat index and the internal temperature during the occupied and unoccupied periods. On the contrary, a strong relationship is reported between the WBGT and RH during the periods (Figure 5). The higher range of heat stress index is calculated in the classroom than the main hall. The study revealed higher humidity values at warm temperature do not have a significant impact on UTCI while higher air speeds at high temperature do have a significant effect on UTCI.

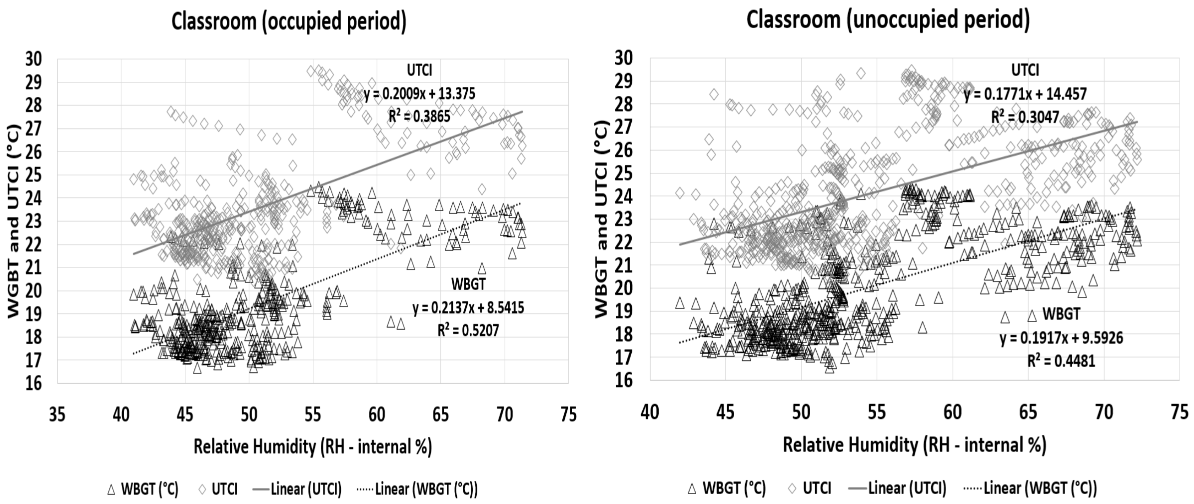


Figure 5. The relationship between the RH and the heat indexes (WBGT and UTCI)

Concerning the spaces (combined), the WBGT and the UTCI were also calculated. The results showed a strong relationship exists between the variables for both periods (Figure 6). The results showed a combination of environmental variables (such as temperature, RH, dew-point temperature) could influence the heat stress indexes. The study showed an increase in the WBGT has a significant effect on the UTCI. Therefore, both heat stress indexes can be used to determine the vulnerability of occupants to heat stress in CLT school buildings with higher values when the UTCI is applied. Although the UTCI has been used for assessing heat stress in outdoor thermal environments, this study showed it could be used in conjunction with the WBGT to evaluate heat stress in various indoor environments.

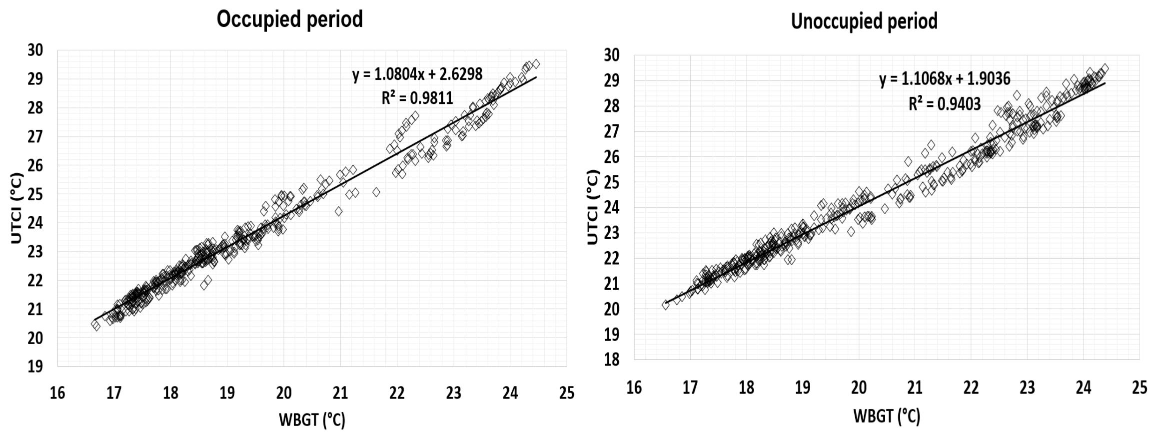


Figure 6. The relationship between the WBGT and the UTCI in the main hall and the classroom

Also, the measured temperatures in the main hall and the classroom were compared to the ASHRAE, the BSEN15251, the CIBSE categories to assess the comfort temperatures and the risk of summertime overheating in the main hall and the classroom. This study showed the temperatures did not exceed the BSEN15251 Cat II upper limit for more than 5% of the time in the classroom (Figure 7). However, the temperatures exceeded the BSEN15251 Cat II upper limit for more than 5% of the time in the classroom during the unoccupied period. The findings on the number of hours above the BSEN15251 that exceeded the Cat II upper limit during the unoccupied period may be a critical concern during the first few hours of occupation in the day-time as additional energy will be required to regulate the thermal environment. The temperatures exceeded all the applicable upper limits of the thermal comfort standards at a higher percentage in the classroom than the main hall. The comfort temperature in the spaces considered in this study was at least 3.0°C lower than the comfort temperature computed from the adaptive model. Comparing the findings from this study with an existing study that focused on thermal comfort in school buildings (Teli et al., 2013), a higher calculated comfort temperature from the adaptive model was noted in this study than the existing research.

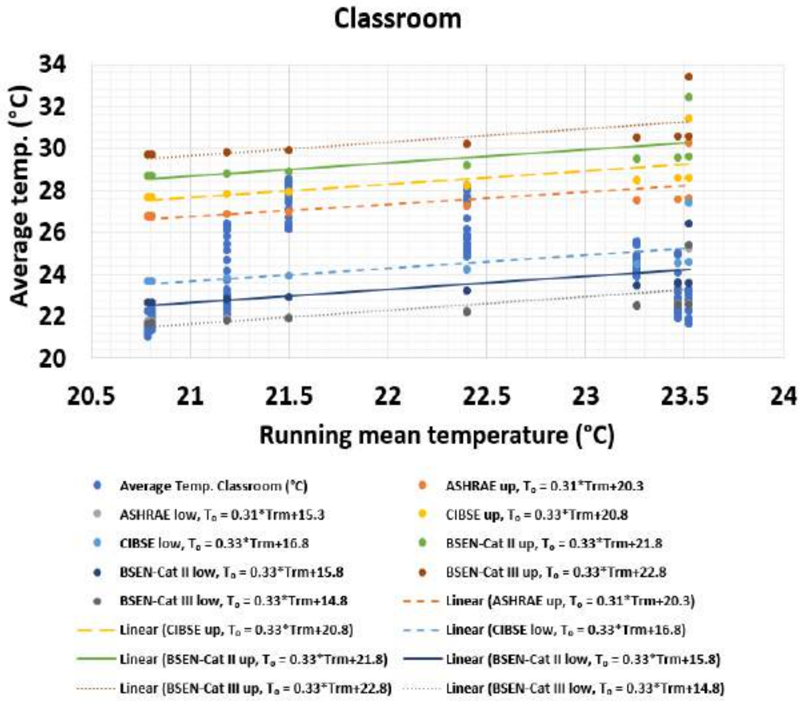


Figure 7. Indoor temperature recorded in the classroom compared to ASHRAE, BSEN15251, CIBSE categories.

6. Conclusions

The research evaluated thermal comfort of occupants and heat stress in CLT school buildings during the occupied and occupied periods in the summertime. The study considered environmental monitoring in the main hall and the classrooms during the summer months (that is, from June-August 2017). The parameters measured at every 60 minutes were analysed. The study showed the average temperature in the main hall on the lower floor (a double-volume space) was 21.2°C; the average dew-point temperature was 16.3°C and the average RH was 73.8%. The average temperature in the classroom on the upper floor was 24.1°C; the average dew-point temperature was 13.8°C while the average RH was 52.8%. The average WBGT varied from 18.8°C to 20.0°C while the average UTCI varied from 21.9°C to 24.0°C. During the occupied period, the average temperatures varied from 23.9°C to 24.2°C. For the occupied and unoccupied periods, the average temperatures range from 21.5°C to 20.9°C. The average WBGT varied from 19.1°C to 19.3°C (occupied period), and it varied from 18.8°C to 20.0°C (unoccupied period). For the mean UTCI, it varied from 19.5°C to 23.4°C (occupied period), and it varied from 21.6°C to 24.0°C (unoccupied period). The temperatures rise above the 28°C threshold for about 4.9% of the time in the classroom while the temperatures rise above the threshold for 4.2% of the time during the occupied period. The findings showed the vulnerability of the occupants to summertime temperatures in the spaces on the upper floor especially when the building is naturally ventilated. Applying the WBGT index and UTCI heat index to determine the heat stress thresholds, the study recommends the WBGT of 19.3°C (occupied) and 20.0°C (unoccupied); the UTCI of 23.4°C and 24.0°C for occupied and unoccupied periods respectively. Overall, the study highlights the WBGT of 19.8°C and UTCI of 23.9°C as possible heat stress indicators for the vulnerable occupants in CLT school buildings. The study revealed a higher UTCI heat stress index than the WBGT index for occupants because higher wind speeds at warm temperatures do not have a significant impact on the WBGT. The study also found out that higher humidity values may not have a significant impact on the UTCI but have a significant effect on the WBGT.

7. Acknowledgement

The author appreciates the school administrators that granted permission to evaluate the school buildings.

8. References

Adekunle, T.O., 2014. Thermal performance of low-carbon prefabricated timber housing. PhD Thesis, *University of Kent*, Canterbury, UK.

Adekunle, T., Nikolopoulou, M., 2014. Post-occupancy and indoor monitoring surveys to investigate the potential of summertime overheating in UK prefabricated timber houses. *In Proceedings of 8th International Windsor Conference,* Cumberland Lodge, Windsor, UK, 10-13 April.

Adekunle, T.O., Nikolopoulou, M., 2016. Thermal comfort, summertime temperatures and overheating in prefabricated timber housing. *Building and Environment*, 103, pp 21-35.

ANSI/ASHRAE Standard 55, 2013. Thermal environmental conditions for human occupancy. *American Society of Heating, Refrigerating and Air-conditioning Eng.*, Atlanta, USA.

ANSI/ASHRAE Standard 62.1, 2013. Ventilation for acceptable indoor air quality. *American Society of Heating, Refrigerating and Air-conditioning Eng.*, Atlanta, USA.

Bernard, T.E., Pourmoghani, M., 1999. Prediction of workplace wet bulb temperature. *Journal of Applied Occupational Hygiene,* 14, pp 126-134

Blazejczky, K., Jendritzky, G., Brode, P., Fiala, D., Havenith, G., Epstein, Y., Psikuta, A., Kampmann, B., 2013. An introduction to the Universal Thermal Climate Index (UTCI). *Geographia Polonica*, 86(1), pp 5-10

Brode, P., Jendritzky, G., Fiala, D., Havenith, G., 2010. The Universal Thermal Climate Index UTCI in operational use. *In Proceedings of the 2010 Windsor Conference*, London, UK, 9 - 11 April 2010.

BSEN15251, 2008. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustic. *BSEN*. Brussels.

CIBSE, 2015. CIBSE Guide A: Environmental design. *Chartered Institute of Building Service Engineers*, UK.

Corgnati, S.P., Filippi, M., Viazzo, S., 2007. Perception of the thermal environment in high school and university classrooms: Subjective preferences and thermal comfort. *Building and Environment*, 42(2), pp 951-959.

Climate Chip, 2016. Analysis tools. http://www.climatechip.org/heat-stress-index-calculation. Accessed om 29/12/2017

DOE, 2015. Increasing efficiency of building systems and technologies. In: An assessment of energy technologies and research opportunities, *Quadrennial Technology Review*, US Department of Energy, September 2015.

EPA, 2012. A brief guide to mold, moisture, and your home. *Environmental Protection Agency (EPA)*, Washington, USA. https://www.epa.gov/sites/production/files/2016-10/documents/moldguide12.pdf

Giridharan, R., 2017. Heat stress in hospital ward spaces: An investigation on a naturally ventilated hospital building in UK. *In proceedings of the 2017 PLEA Conference*, Edinburgh, UK, 3 - 5 July 2017, Volume 3, pp 3762-3769.

Hussein, I., Rahman, M.H.A., 2009. Field study on thermal comfort in Malaysia. *Eur. J. Sci. Res.*, 37(1), pp 134-152.

Hwang, R-L., Lin, T-P., Kuo, N-J., 2006. Field experiments on thermal comfort in campus classrooms in Taiwan. *Energy and Buildings*, 38(1), pp 53-62.

Hwang, R-L., Lin, T-P., Chen, C-P., Kuo, N-J., 2009. Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan. *Int.l Journal of Biometeorology*, 53(2), pp 189-200.

Pereira, D.L., Raimondo, D., Corgnati, S.P., da Silva, M.G., 2014. Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: methodology and results. *Build. and Environ*, 81, pp 69-80.

Katafygiotou, M.C., Serghides, D.K., 2014. Thermal comfort of a typical secondary school building in Cyprus. *Sustainable Cities and Society*, 13, pp 303-312.
Lemke, B., Kjellstrom, T., 2012. Calculating workplace WBGT from meteorological data: A tool for climate change assessment. *Industrial Health*, 50, pp 267-278.
Liang, H-H., Lin, T-P., Hwang, R-L., 2012. Linking occupants' thermal perception and building thermal performance in naturally ventilated school buildings. *Applied Energy*, 94, pp 355-363.
Lomas, K.J., Giridharan, R., 2012. Thermal comfort standards, measured internal temperatures and thermal resilience to climate change of free running buildings: a case study of hospital ward. *Building and Environment*, 55, pp 57-72.
Montazami, A., Nicol, F., 2013. Overheating in schools: comparing existing and new guidelines. *Building Research & Information*, 41(3), pp 317-329.
Mors, S-t., Hensen, J.L.M., Loomans, M.G.L.C., Boerstra, A.C., 2011. Adaptive thermal comfort in primary school classrooms: creating and validating PMV-based comfort charts. *Build. and Environ.*, 46(12), pp 2454-2461.
Nguyen, J.L., Schwartz, J., Dockery, D.W., 2014. The relationship between indoor and outdoor temperature, apparent temperature, relative humidity, and absolute humidity. *Indoor Air*, 24(1), pp 103-112.
NEHC, 2007. Prevention and treatment of heat and cold stress injuries. *Navy Environmental Health Centre* (NEHC), USA.
NHS, 2011. Heatwave plan for England: protecting health and reducing harm from extreme heat and heatwave. Best practice guidance. *National Health Service*, London.
Nicol, F., Humphreys, M., 2007. Maximum temperatures in European office buildings to avoid heat discomfort. *Solar Energy*, 81, pp 295-304.
NIOSH, 2015. Indoor environmental quality. *The National Institute for Occupational Safety and Health (NIOSH)*. https://www.cdc.gov/niosh/topics/indoorenv/temperature.html.
Osczevski, R., Bluestein, M., 2005. The New Wind Chill Equivalent Temperature Chart. *Bulletin of the American Meteorological Society*, 86(10), pp 1453-1458
OSHA, 2016. *Minnesota Department of Labor and Industry.* Occupational Safety and Health Division, Minnesota. www.dli.mn.gov
Rupp, R.F., Vasquez, N.G., Lamberts, R., 2015. A review of human comfort in the built environment. *Energy and Buildings*, 105, pp 178-205.
Serghides, D.K., Chatzinikola, C.K., Katafygiotou, M.C., 2014. Comparative studies of the occupants' behaviour in a university building during winter and summer time. *Int. J. of Sustainable Energy*, 34(8), pp 528-551
Stull, R., 2011. Wet-Bulb Temperature from relative humidity and air temperature. *J. Appl. Meteor. Climatol.*, 50, pp 2267-2269
Teli, D., Jentsch, M.F., James, P.A.B., 2012. Naturally ventilated classrooms: an assessment of existing comfort models for predicting the thermal sensation and preference of primary school children. *Energy and Buildings*, 53, pp 166-182.
Teli, D., James, P.A.B., Jentsch, M.F., 2013. Thermal comfort in naturally ventilated primary school classrooms. *Building Research & Information*, 41(3), pp 301-316.
Teli, D., Jentsch, M.F., James, P.A.B., 2014. The role of a building's thermal properties on pupils' thermal comfort in junior school classrooms as determined in field studies. *Building and Environment*, 82, pp 640-654.
UTCI. The Universal Thermal Climate Index. www.utci.org
Yau, Y.H., 2008. A preliminary thermal comfort study in tropical buildings located in Malaysia. *International Journal of Mechanical and Materials Engineering*, 3, pp 119-126.
Zhang, Y., Wang, J., Chen, H., Zhang, J., Meng, Q., 2010. Thermal comfort in naturally ventilated buildings in hot-humid area of China. *Building and Environment*, 45(11), pp 2562-2570.
Zhang, Y., Chen, H., Meng, Q., 2013. Thermal comfort in buildings with split air-conditioners in hot-humid area of China. *Building and Environment*, 64, pp 213-224.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Effect of Operational energy variations on life cycle energy: An evaluation in residential apartments

Akshay Kumar Bishnoi[1], Soumya R.[1], Dr. Rajasekar Elangovan[2]

[1] Larsen & Toubro, Engineering Design & Research Center (EDRC), Buildings & Factories IC, L&T Construction Ltd., Chennai, India, email: bishnoiaks@lntecc.com; ssoumyaa@lntecc.com;
[2] Indian Institute of Technology – Roorkee (IIT – R), India, email: erajas@gmail.com

Abstract: This paper deals with characterization of operational energy in a group of apartment buildings and its impact on the life cycle energy (LCE) predictions. Field investigations covered eight apartment buildings with 656 residential units representing three spatial types located in a hot-humid climatic zone of India. The residences were predominantly naturally ventilated, but used air-conditioners during peak summer. Data collected include monthly electrical energy consumption for four-year duration and primary field surveys focused on the characteristics of connected appliance loads, operational patterns, type of air-conditioning system and their operating conditions. The overall average energy performance index (EPI) of the residential units is 32.4 kWh/m^2/year. Comfort conditioning had a major contribution in operational energy use which is evident from a strong correlation (r^2=0.85) between monthly energy consumption and monthly mean outdoor temperature ($T_{out-\mu}$). The magnitude of variation in energy consumption among residential types is found to be lesser during winter than summer attributed to the diversities in air conditioner usage during this season. Factors such as orientation, height at which the residence is located, mutual shading by adjacent buildings and operational patterns had a statistically significant impact on the operational energy consumption. However, the impact of subjective preferences and operational characteristics had a much stronger impact on the energy use. Statistical cluster analysis of the data indicated the presence of three distinct clusters representing low, mid and high consumption residences. The residential units were found to be distributed in these clusters irrespective of their spatial typology. Life cycle energy per residential unit is 1688.4 x10^3 MJ out of which EE contributes 627.7x10^3 MJ (37%) and operational energy contributes 1060.7 x10^3 MJ (63%) for a 50-year life span. Mean LCE of low, medium and high consumption clusters are 1424.9 x10^3 MJ/home, 1931.1x10^3 MJ/home and 2386.3x10^3 MJ/home respectively. The results indicate a strong influence of subjective variations in building operations on the life cycle energy.

Keywords: Life Cycle Energy, Operational Consumption, Embodied Energy, Energy Performance Index, Clustering Analysis

1. Introduction

Life cycle energy (LCE) of a built space comprises of a relatively static embodied energy component and a dynamic operational energy component. Energy associated with manufacture, transportation, installation, maintenance and demolition are the critical dimensions which determine embodied energy sequestrated in built spaces (Dixit, 2010). Environmental boundary conditions, building design, operational patterns and inter-personal variables of occupants are the critical dimensions which determine the operational energy outlay during service life (Ioannou, 2015; Hemsath, 2015; Wang, 2015). Based on an extensive literature review, Cabeza et al (2014) highlight five distinct challenges involved in construction-related carbon foot-print assessment – site-specific impacts, model complexity, scenario uncertainty, indoor environments and inclusion of recycled material data. Erlandsson and Borg (2003) suggest that a sequential life-cycle approach is essential to evaluate the embodied energy while operational energy can be treated as a continual process.

The contribution of embodied energy and operational energy in the life cycle energy of a building varies contextually. This depends on building type, mode of operation as well as severity of the boundary conditions. A review of 73 LCE studies presented by Ramesh et al (2010) showed that operational energy had a major share (80-90%) in LCE. Studies such as Thormark (2002), Yohanis and Norton (2002) and Pinky Devi and Sivakumar (2014) showed that the share of embodied energy can be more than a third of LCE. Mohammed et al (2013), through a review of literature, highlights the significance of embodied energy in LCE. Studies on vernacular residences in India (Praseeda, 2014) show that the contributions vary significantly based on construction technologies as well as the thermal comfort preferences of the occupants. Developments in the field of thermal adaptation (Yang, 2013) have emphasized that occupants are catalysts in the building operations rather than passive recipients and constitute the prime-movers of operational energy use. Residential spaces hold a tremendous potential for thermal adaptation, which in a way, offers immense potential for energy savings. However, the amount of subjectivity involved in thermal adaptation tenders difficult the generalization of this mechanism and its impacts. In the Indian context, residential buildings in India are conceived as naturally ventilated spaces during design stages with intermittent use of ceiling fans to enhance ventilation. Comfort conditioning, typically a direct expansion system (window or split air-conditioning unit), becomes an add-on. Socio-cultural diversities in urban dwellers lead to differences in thermal preferences and comfort (Chappells, 2005), resulting in operation energy use variations. These factors consequently lead to an increased level of uncertainty in the life-cycle-energy predictions. In the absence of evidence-based data on actual environmental impact of these developments, the industry risks itself in setting either self-complacent or practically irrelevant benchmarks.

2. Objective and Methodology

In this context, the objectives of the study are to

(a) Characterize the operational energy use of residential apartments and identify the factors affecting it,

The scope of the study is limited to the operational energy consumption within residential units and excludes common services like vertical transportation, outdoor lighting and landscaping. Embodied energy assessment is limited to the residential blocks including the substructure, but excludes roads and non-residential structures like community amenities. The study involves real-time operational energy data collection accompanied by subjective field surveys for investigating the pattern of utility energy consumption. Effect of various factors influencing operational energy consumption is analyzed through characterization studies. Factors such as residential type, exposure condition of residential units, mutual shading by adjacent apartment blocks, height at which the residence is located and other personal variations which affect the operational energy consumption are considered in the study. Based on the drawings and bill of quantities and supportive field data, a building information model is prepared using which embodied energy is estimated. Considering a service life of 50-years life cycle energy (LCE) is evaluated. The impact of factors which affect operational energy consumption on LCE is analyzed. A set of energy efficiency measures are simulated and their impact on LCE as well as operational cost-benefits is presented.

3. Description of the study area

The study area is a residential enclave comprising of 656 residential units located in the sub-urban area of Chennai, India (13.1°N, 80.3°E). Chennai represents a hot-humid climate. Fig. 1 presents the summary of annual temperature and humidity variations.

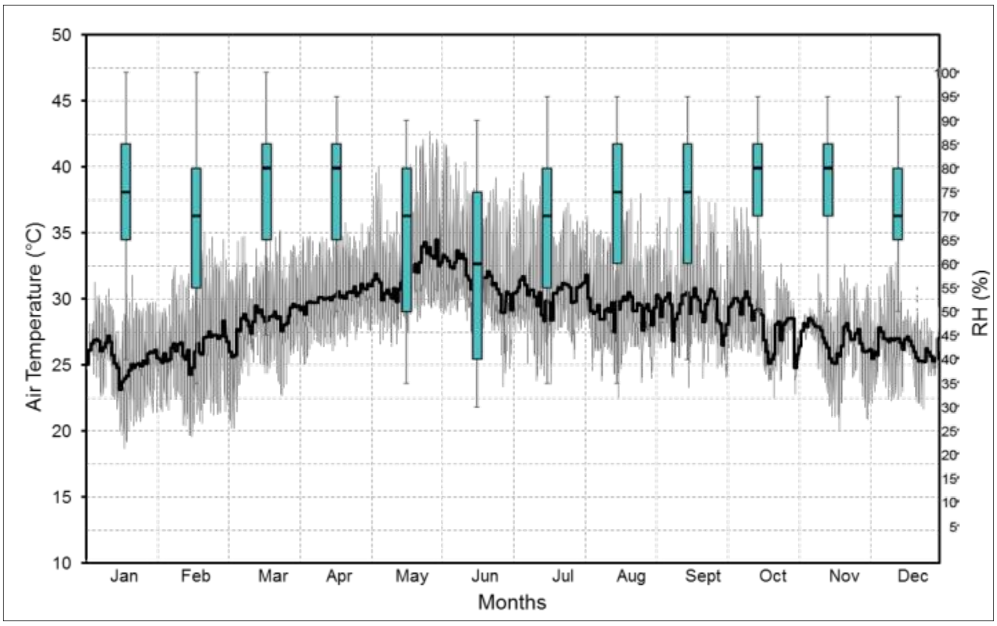


Figure 1: Summary of climatic conditions

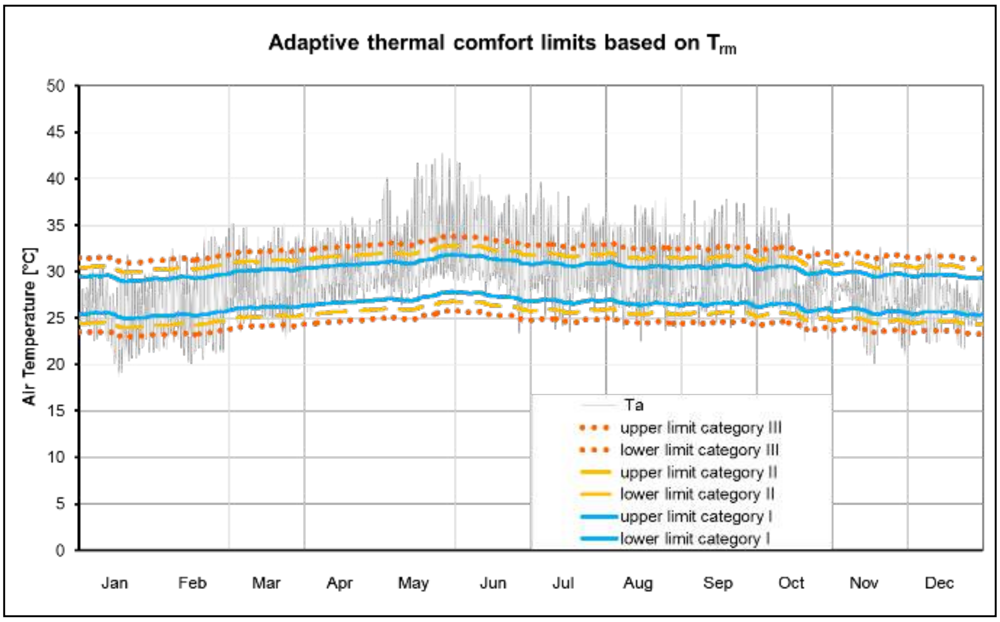


Figure 2: Adaptive comfort limits

The daily mean outdoor temperature ($T_{out\text{-}\mu}$) varies from 23°C to 28°C in winter and 30°C to 35°C in summer with a peak T_{out} of 42°C during the month of May. The average diurnal difference (ΔT_{out}) varies from 10°C in summer to 8°C in winter. Relative humidity varies between 35-90% (an inter-quartile range of 40-75%) during summer and 50-90% (an inter-quartile range of 65-85%) during winter. Daily average solar radiation on a horizontal plane varies form 100 W/m^2 during summer to 180 W/m^2 during winter. Adaptive thermal comfort limits determined based on the running-mean outdoor temperature (T_{rm}) (Rajasekar, 2010) is presented in Fig. 2.

The residential units are distributed across eight apartment blocks which are 14-storey high. The enclave comprises of three types of residential units - type I, type II and type III with carpet areas 96 m^2, 121 m^2 and 144 m^2 respectively. Type I units have two bedrooms while type II and III have three bedrooms each. The superstructure is constructed with a combination of reinforced concrete shear-wall and block-masonry infill system. The substructure includes a raft footing and two basements which accommodate parking spaces and mechanical pumping rooms. Fig. 3 shows the site plan of the enclave.

Figure 3: Site plan of the study area

A subjective field survey on utility electrical energy consumption is administered in the residential community. The survey focused on household size, occupancy pattern, and major electrical appliances contributing to the connected load, capacity and usage pattern of appliances. The average household size in enclave is found to be 3.5 persons per residential unit. The availability of appliances, especially air-conditioning units and their efficiencies are found to vary based on the residential typology. Type-III residential units predominantly have two - three direct expansion air-conditioning units (split AC system). Type I and II residences have one - two such units. Diversity in the operational pattern of air-conditioners is evident in terms of variations in set-temperature which ranges from 18 to 28^{o}C during summers (SD: 2.1) and the operational duration which ranges from 3 to 15 hours (SD: 1.2). The mean value of set point temperature obtained through the survey is 23.8^{o}C and daily operational duration is 6.5 hours for summer season. A majority of (about 60%) air-conditioning units have 2 and 3-star ratings of the bureau of energy efficiency, India which corresponds to an EER of 2.7 – 3.1.

4. Characterization of Operational Energy use

Real-time monthly operational energy data of 656 residential units for a period of three years has been collected from electricity regulatory authority (TANGEDCO). Based on a preliminary statistical analysis, outliers (95% CI limits) in data has been eliminated. This process limits the sample size of the study to 494 residential units (174 type I, 162 type II and 158 type III units).

The overall average energy performance index (EPI) of the residential units calculated from the above data is 32.4 kWh/m^2/year (Fig. 4). This amounts to a per-capita energy consumption of 1288 kWh/year which compares well with the state's average (Annual Report, 2014). The EPI is about 33% lower than that of a similar study reported in the composite climate of India (BEE 2014) Type-I units consume relatively lesser energy (EPI=28kWh/m^2/year) and the consumption pattern exhibits a relatively less distribution compared to type II and III units. Type II and III units exhibit similarity in energy consumption with an EPI of 37 kWh/m^2/year and 34.1 kWh/m^2/year respectively. Fig. 5 shows the typology-wise distribution of annual electricity consumption. It can be noted that the energy consumption of type II units is lower (mean: 3036 kWh) than type III units (mean: 3256 kWh). However, the EPI of type II is higher than type III by virtue of the floor area variations. This highlights the fact that EPI benchmarks of such naturally ventilated residential buildings need to be normalized if they include dissimilar residential building typologies.

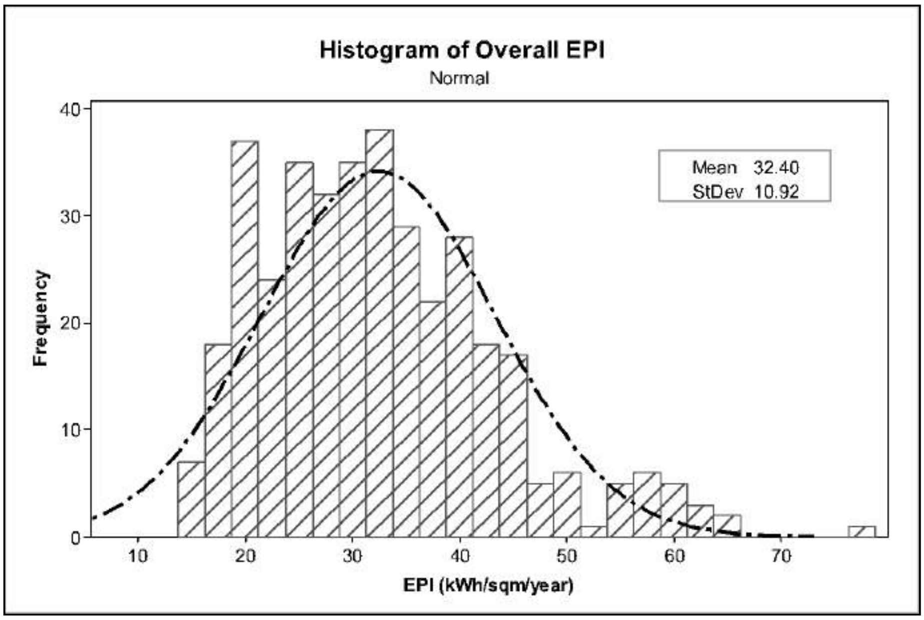


Figure 4: Histogram of overall EPI

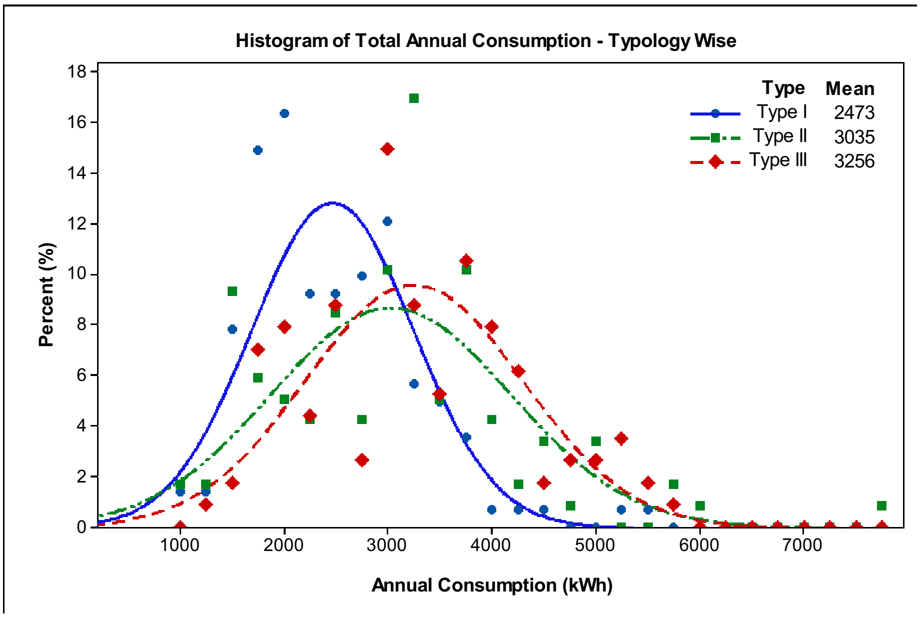


Figure 5: Summary of typology-wise energy consumption

In this study, operational energy consumption during peak winter (December) represents the utility load excluding air-conditioners. When this value is deducted from the energy consumption of other months, it can provide an indicative estimate of energy consumption for space cooling. It needs to be noted that, the residential community sourced hot water from the roof-top solar heaters and the climatic condition did not demand space heating. Hence, winter utility consumption referred above excludes any heating related energy use.

5. Factors influencing operational energy consumption

Monthly energy consumption shows a strong correlation (r^2=0.85) with the monthly mean outdoor air temperature ($T_{out-\mu}$) as shown in fig. 6. Typology wise variation of energy use with respect to $T_{out-\mu}$ is shown in fig. 7.

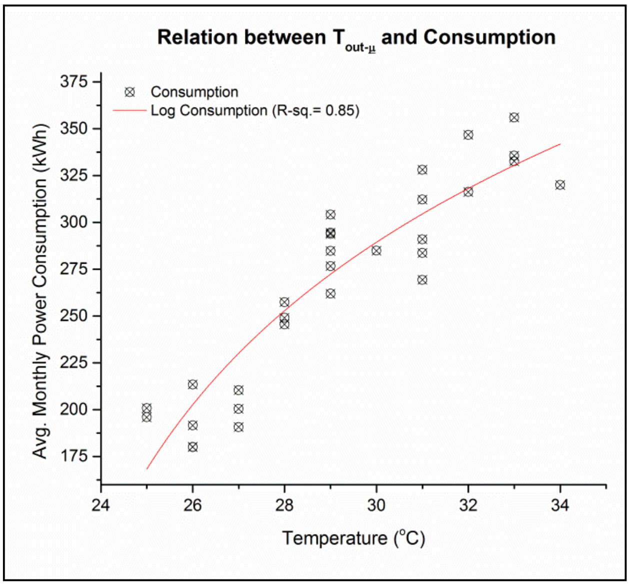


Figure 6: Relation between Tout-µ and energy consumption

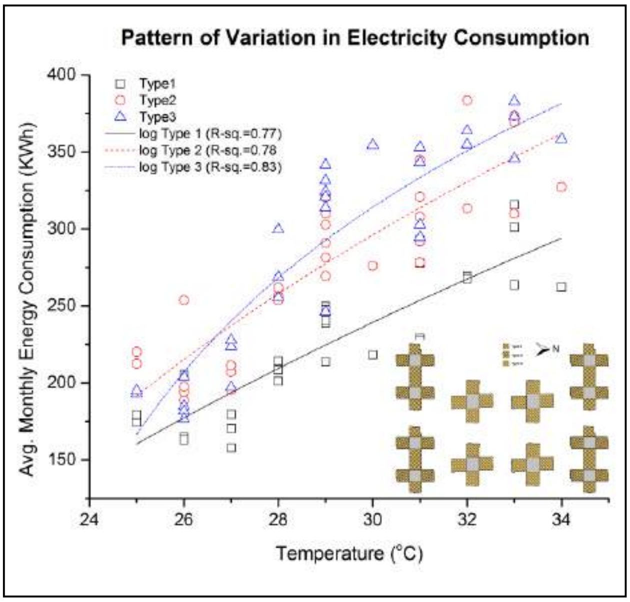


Figure 7: Relation between Tout-µ and typology variations

The magnitude of variation in energy consumption among residential types is found to be lesser during winter than summer. This is attributed to the diversities in air conditioner usage which includes the number of air conditioners being operated, duration of use and set-point temperatures. Annual energy consumption of type I residential units is relatively lesser than type II and III units. During winter, type II units have a marginally higher (25kWh) energy than type III while a reversal of this trend is observed during summer. A two-factor analysis of variance indicates a significant effect of building typology on the energy consumption $F(2,9)=51.8$, $p<0.01$. Similarly, the effect of $T_{out-\mu}$ on energy consumption is statistically significant ($F(2,9)=48.7$, $p<0.01$). The energy consumption pattern during summer (April-June) exhibits higher distribution compared to winter as shown in fig. 8 and 9.

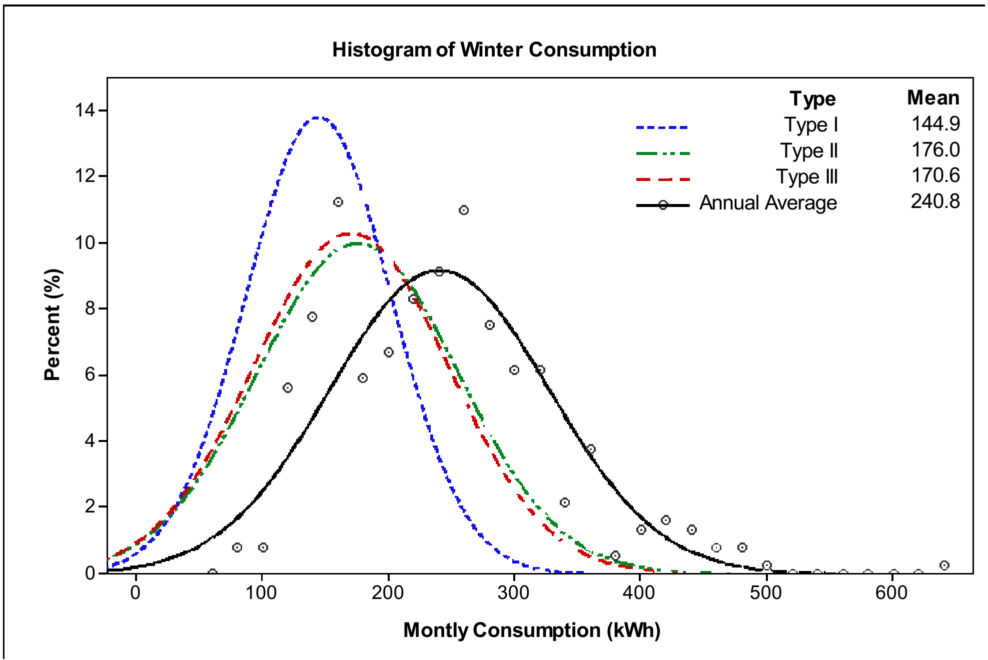


Figure 8: Statistical summary of monthly energy consumption for Summer

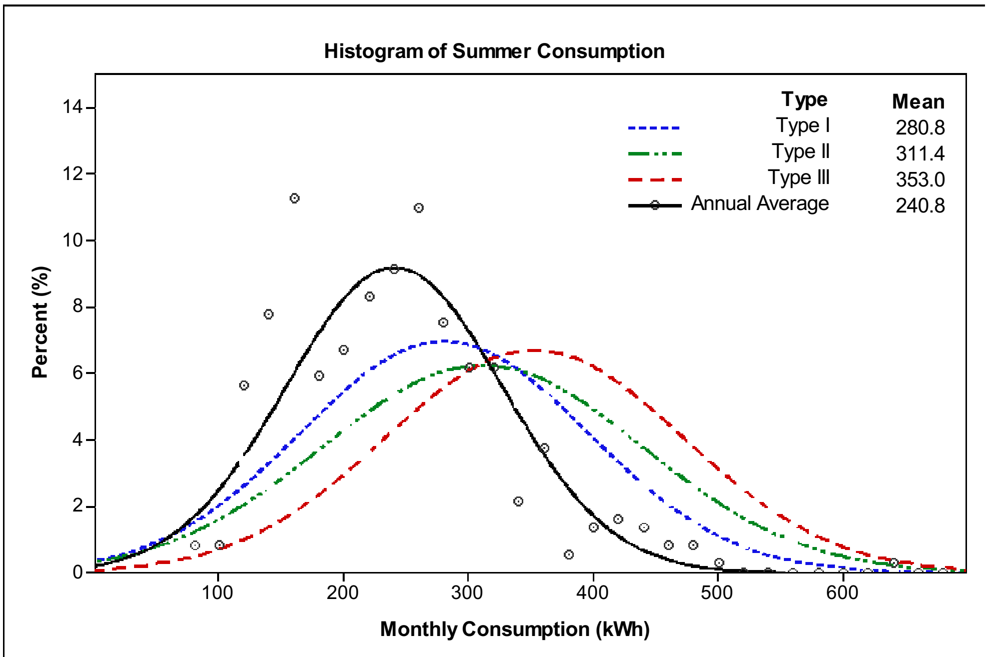


Figure 9: Statistical summary of monthly energy consumption for Winter

In order to analyze the effect of orientation on energy consumption, data for 375 residences (97 type I, 140 type II and 138 type III units) are analyzed. According to the architecture design layout, each residential unit has three exposed facades – North-East-South (NES), North-West-South (NWS), East-North-West (ENW) or East-South-West (ESW). Fig. 10 (a & b) shows the relation between $T_{out-\mu}$ and energy consumption for the above four exposure conditions.

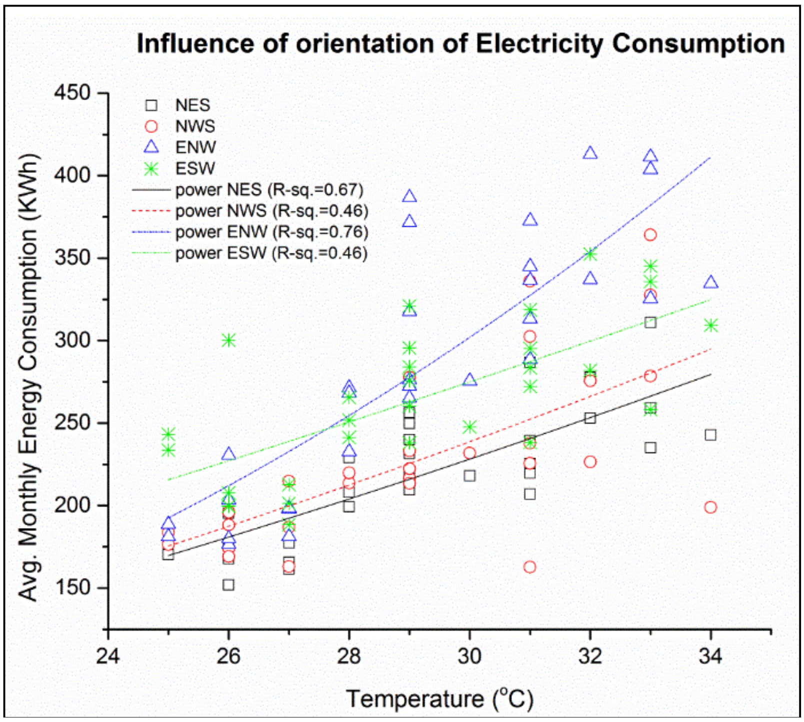


Figure 10 (a): Influence of orientation on operational energy consumption

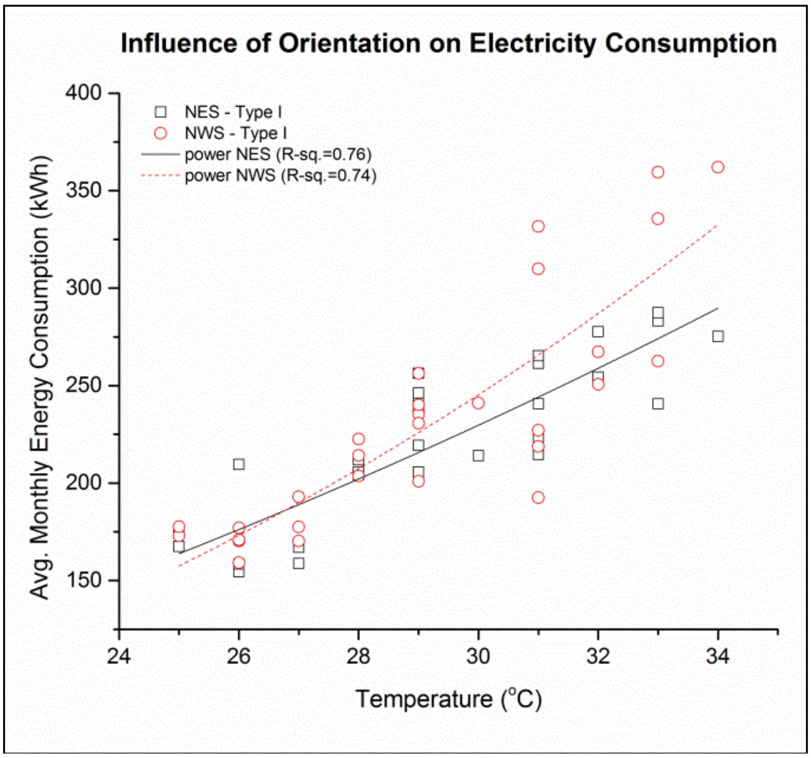


Figure 10 (b): Influence of orientation on operational energy consumption

A two-way analysis of variance comparing the influence of $T_{out-\mu}$ and orientation yields a main effect of orientation $F(3,9)=19.4$, $p<0.01$, such that energy consumption is significantly different for four exposure conditions. The variations are in the following sequence – NES (μ=218.8, SD=39.8) < NWS (μ=228.6, SD=52.1) < ESW (μ=265.3, SD=45.4) < ENW (μ=285.3, SD=76.4). Irrespective of the orientation being considered, $T_{out-\mu}$ has a significant effect ($F(3,9)=22.5$, $p<0.01$) on energy consumption. Energy consumption of units with north and south exposure (NES, NWS) have relatively lower energy consumption compared to those with east and west exposure (ENW, ESW). ENW and ESW exhibit a phase-shift in their consumption between winter and summer. This is attributed to the solar geometry (13.1^{o}N latitude) based on which northern facades experience direct solar incidence during summer and southern facades during winter.

The spacing between two adjacent apartment towers vary between 12m to 19m which provides a height to spacing ratio of 2.8 to 2.2. Consequently, the mid and lower floors experience a mutual shading effect by neighboring apartment towers. The intensity and duration of shadowing varies based on the azimuth and altitude angles of the sun. Fig. 11 show the shadow range during summer and winter solstice respectively.

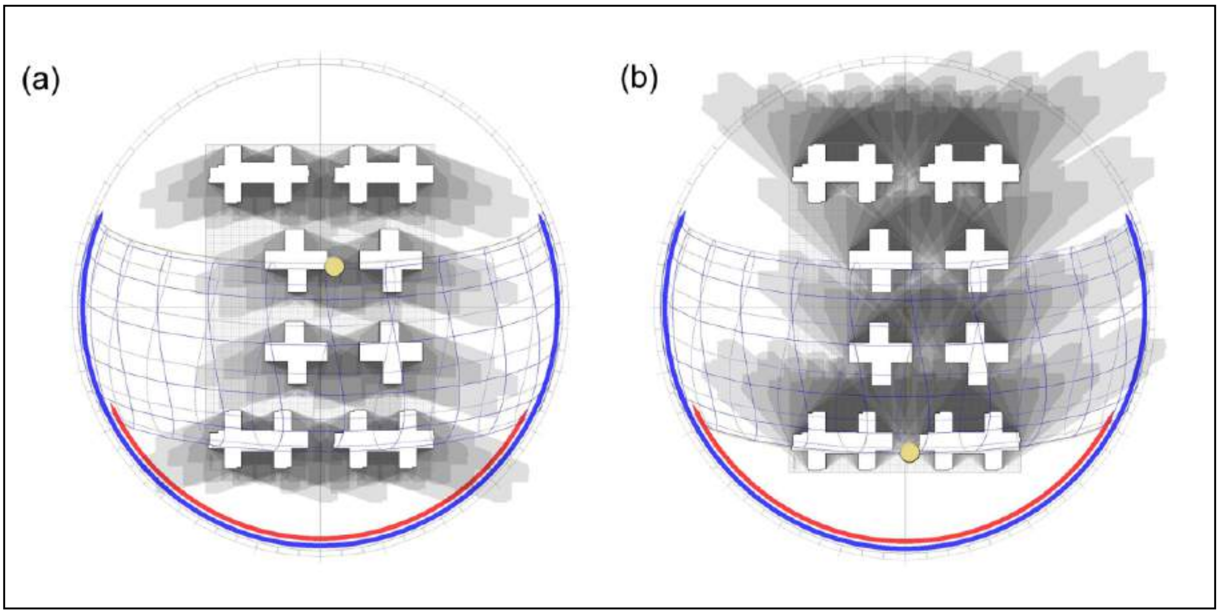


Figure 11: Shadow range analysis of the residential enclave (a) Summer (b) Winter

A solar incidence analysis indicated that exposed and mutually shaded facades exhibited a significant difference in terms of insolation levels. This was more prominent on the east and west facades of residential units located in 1st to 6th floor levels. However, the difference in operational energy consumption due to the mutual shading effect was found to be marginal as shown in fig. 12. An ANOVA test on energy consumption of shaded and unshaded groups indicate no significant variation between the groups.

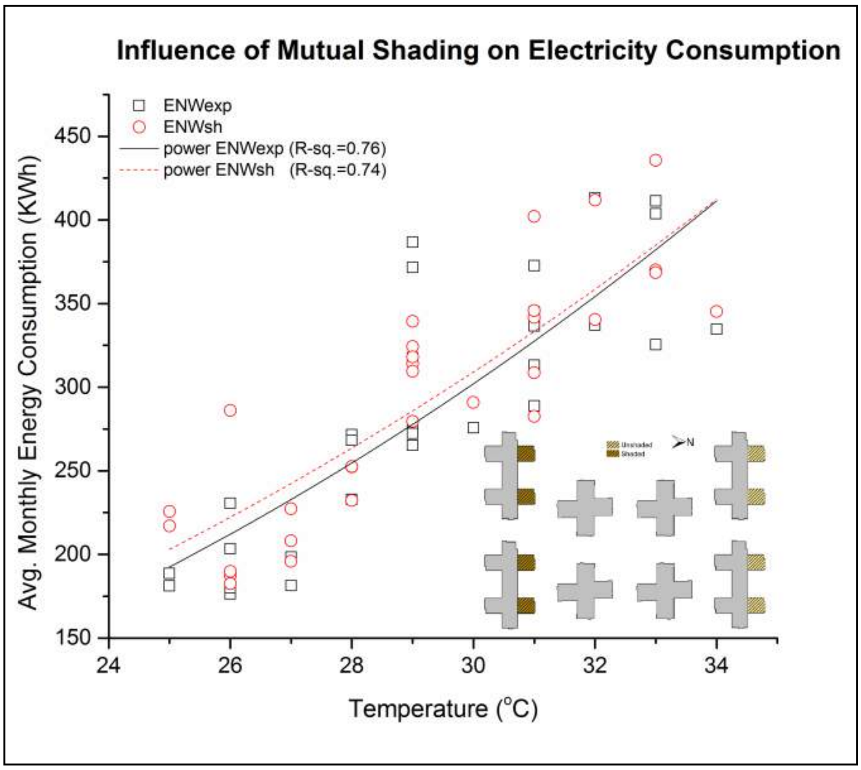


Figure 12: Influence of Mutual shading on operational energy consumption

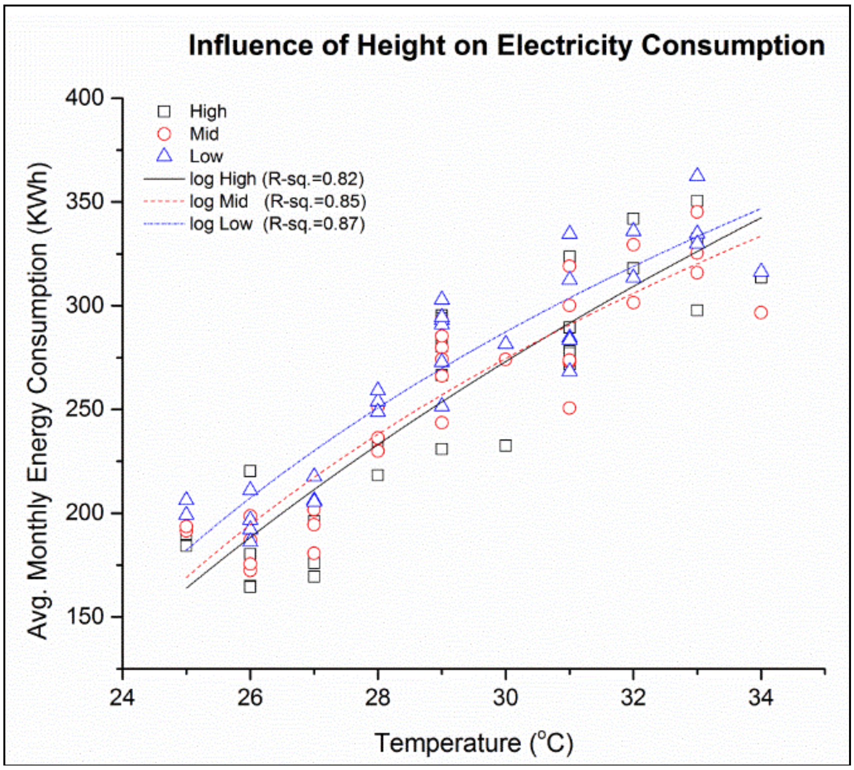


Figure 13: Influence of Height on operational energy consumption

In order to study the effect of height on energy consumption, a comparative evaluation of 90 residential units is carried out. For this purpose, residential units located in 9-12 floor level (high), 7-10 floor level (mid) and 2-5 floor level (low) are considered. The topmost floor, with an exposed roof has not been considered for this analysis. A two-factor analysis of variance shows a significant effect of height on energy consumption ($F(2,9)=4.7$, $p<0.01$). The variation is such that high floor residences consume relatively lesser energy (μ=253kWh, SD=57) compared to the lower floors (μ=268kWh, SD=52). The effect of $T_{out-\mu}$ on energy consumption is statistically significant. Fig. 13 shows the trend in consumption with respect to $T_{out-\mu}$ variations. At higher ambient temperatures, energy consumption of upper floor residences closely converges with that of lower floors. At a lower ambient temperature, the residential units at higher floors consumed slightly lesser energy than that of lower floor units. Studies in this region (Rajasekar, 2010; TV, 2014) have highlighted the limitations in thermal adaptation and fenestration operation due to concerns of visual privacy, pollution and bugs. Real-time field measurements of indoor thermal characteristics in the apartments showed that indoor air velocities increased significantly with the floor height (μ=0.3m/s in the 2nd floor, μ=0.65m/s in the 13th floor). Though the trend of higher energy consumption in lower floor levels can be related to these factors, further studies are required for a conclusive interpretation.

Though the energy consumption varied with respect to typology of residential units, a wide distribution is observed within the groups. In order to investigate the effect of other personal factors on energy consumption, a statistical cluster analysis is performed with the complete data set. Based on this analysis the data is classified into three distinct clusters denoting low, medium and high energy consumption. The mean monthly energy consumption of low, medium and high consumption clusters are 404 kWh, 636 kWh and 852 kWh respectively. Table 1 presents a summary of the three clusters.

Table 1: Summary of the statistical cluster analysis of operational energy consumption

		Low consuming	**Medium consuming**	**High consuming**
	% share	**59.10%**	**31.80%**	**9.10%**
Season		Mean of cluster	Mean of cluster	Mean of cluster
Winter	**Dec-Jan**	278	362	654
	Feb-March	330	479	797
Summer	**April-May**	466	787	921
	June-July	495	838	920
	Aug-Sept	454	771	991
Monsoon	**Oct-Nov**	398	581	827
		Percentage share in low consuming	Percentage share in medium consuming	Percentage share in high consuming
	Type I	78%	18%	4%
	Type II	48%	40%	12%
	Type III	51%	34%	15%

The analysis indicates that high consuming residences amounts to only 9.1% of the total while low consuming residences amounts to about 59%. A wide difference in the energy consumption pattern among residences irrespective of their dwelling typologies is evident from table 1. For instance, about 4% of type I units are represented in the high consumption category, and 18% in the medium consumption category. There is only a marginal difference between the consumption pattern of Type II and type III units. Variation in energy consumption with respect to the outdoor temperature for the three clusters is shown in fig. 14. Normalized mean EPI for the high, medium and low consumption clusters are 20.6 kWh/m^2/year, 30.4 kWh/m^2/year and 39.5 kWh/m^2/year respectively.

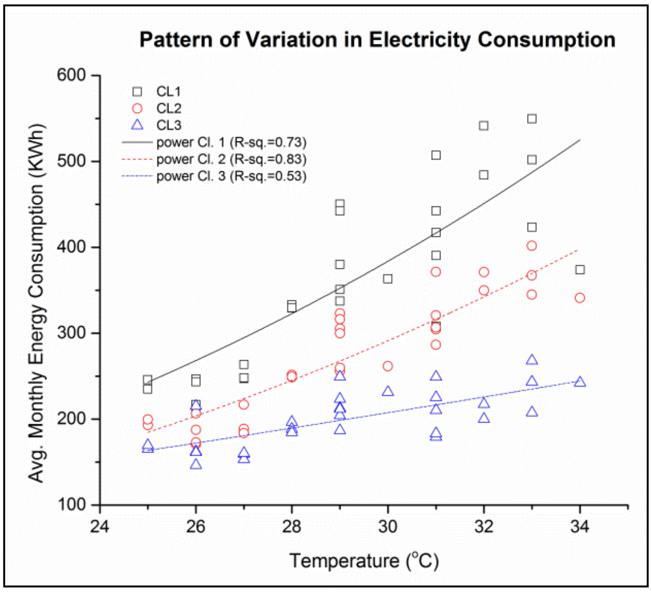


Figure 14: Cluster-wise variation in energy use

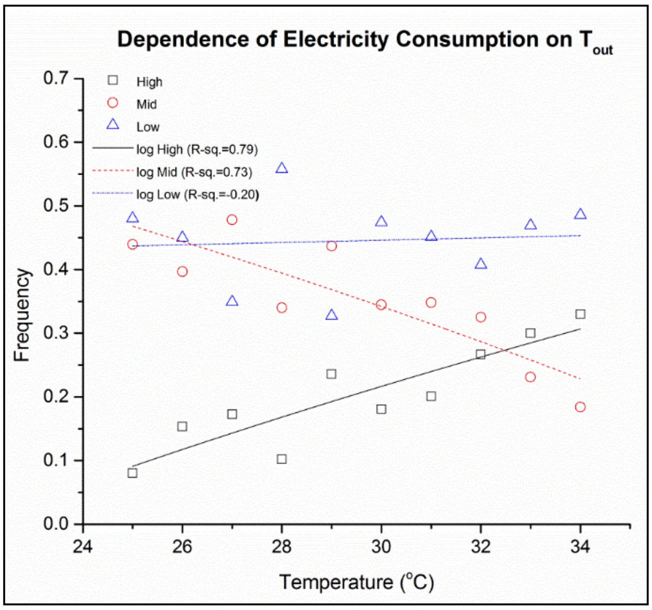


Figure 15: Logit analysis of cluster population

Logit analysis is carried out (fig. 15) to compare the trend in energy consumption of the three clusters relating to T_{out} variations. The proportion of high consuming residential units is found to be directly proportional to the increase in T_{out} (r^2=0.79). On the other hand, the proportion of low consuming units is found to be inversely proportional (r^2=0.73) to the increase in T_{out}. The proportion of medium consuming units did not vary significantly with respect to T_{out} variations.

6. Embodied energy assessment

For the purpose of embodied energy (EE) assessment, cradle to gate approach (excluding post-life disposal) has been adopted. A building information model is developed based on as-built drawings obtained from the construction and facility management teams. The quantity estimates obtained from this model as well as from the bill of quantities of architectural and civil items are used in EE calculations. EE factors have been adopted from standard international databases (ICE, 2017). Embodied energy presented in this paper does not include construction process and site equipment. The embodied energy of the residential enclave is 3.16 $x10^3MJ/m^2$ including of the substructure and two basements. EE for type I, II and III units are 4.12 $x10^3MJ/m^2$, 3.87 $x10^3MJ/m^2$ and 3.96 $x10^3MJ/m^2$ respectively. In other words, type I, II and III residential units have an EE value of $400x10^3$ MJ/house, 473.2 $x10^3$MJ/house and $570.3x10^3$MJ/house respectively.

7. Impact of operational energy variations on life cycle energy

Life-cycle energy (LCE) of the residential units are estimated based on the real-time operational energy and embodied energies presented in the previous sections. The LCE excludes non-electric household cooking fuel, vehicular fuel and other tertiary energy usages. Based on the data obtained from the facility management team, an annual increment of 0.1% is applied to embodied energy. This is termed as recurring embodied energy which accounts for replacement, refurbishment and repairs. The life cycle energy per residential unit is $1688.4x10^3$MJ out of which EE contributes $627.7x10^3$MJ (37%) and operational energy contributes $1060.7x10^3$MJ (63%). The embodied to operational energy ratio is 0.59:0.41 at the end of a 25-year life span and 0.37:0.63 at the end of a 50-year life span. A split-up of operational energy in terms of utility and cooling operational energy and EE in terms of initial and recurring embodied energy is presented in fig.16. Consumption relating to space cooling forms a major share of operational energy consumption.

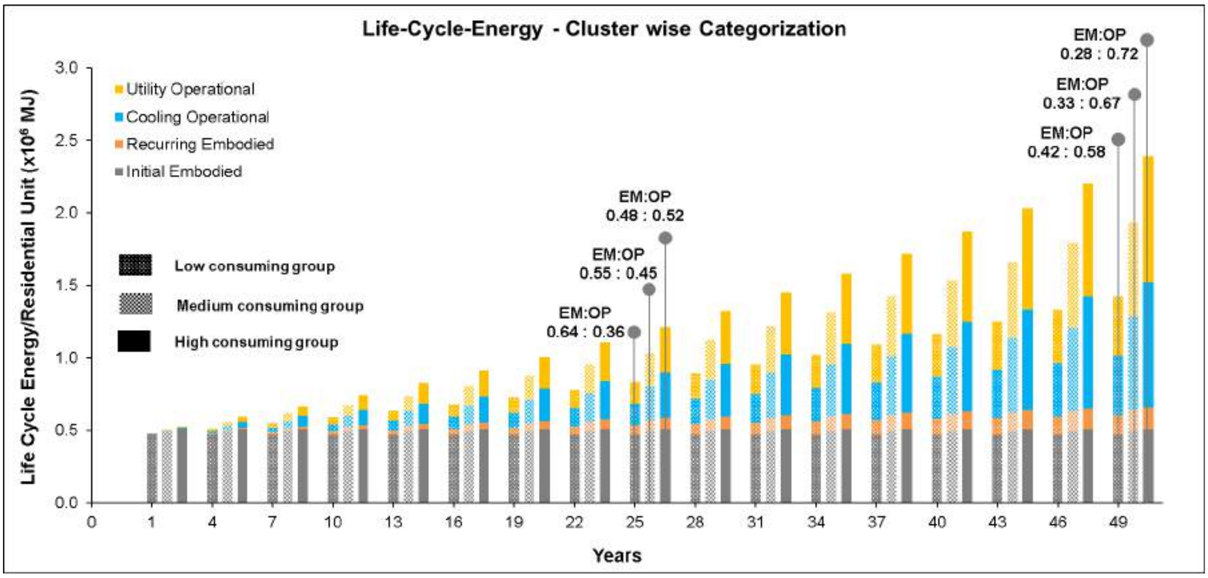


Figure 16: Cluster-wise categorization of LCE

Fig. 16 also compares the LCE of the three residential clusters discussed in the earlier section. The mean operational energy of the three clusters is considered for this computation. With respect to EE, a weighted-mean value is calculated based on the distribution of type I, II and III units in low, medium and high consumption categories (table 1). The LCE values described in fig. 16 represent the mean value of low, medium and high consuming residential units. Mean LCE of low, medium and high consumption clusters are 1424.9 $x10^3$MJ/home, $1931.1x10^3$MJ/home and $2386.3x10^3$MJ/home respectively. LCE of medium and high consumption clusters are 26% and 40% higher as compared to the low consumption cluster. The contribution of operational energy to the LCE for medium consumption cluster is 9% higher than the low consumption cluster. Similarly, it is 14% higher for a high consumption cluster compared to the low consumption cluster. These results highlight the possible variations in life cycle energies due to operational patterns within as well as across residential typologies.

8. Conclusion

The paper presented a characterization assessment of operational, embodied and life cycle energies for a residential enclave. Real-time operational energy data is characterized based on residential typology and the influence of various factors affecting operational energy use. Average EPI of 32.4 kWh/m^2 and per-capita energy consumption of 1288 kWh/year is obtained through the study. About 30% variation in EPI is noted between residential types (type I and II). Though total energy consumption of type III residential units (floor area: 144m^2) are higher compared to type II units (floor area: 121m^2) the EPI of type III units are lower than type II. Hence caution should be exercised while denoting energy consumption in terms of EPI especially when dissimilar building typologies with floor area variations are being compared. A 30% difference in summer operational energy consumption is noticed between residences with critical and non-critical exposures. During winter the difference is however, minimal. This consequently resulted in 7% increase in LCE of residential units with critical exposure as compared to those with non-critical exposure. With a height to spacing ratio of 2.8 to 2.2 between adjacent residential blocks, the effect of mutual shading on operational energy consumption is found to be statistically insignificant. The height at which a residential unit is located is found to affect operational energy consumption (about 6% variation). However, its impact on the LCE is found to be insignificant. A statistical cluster analysis of the data indicated the existence of three distinct clusters representing high, medium and low consumption residences. Normalized mean EPI for high, medium and low consumption clusters established through the study are 20.6 kWh/m^2/year, 30.4 kWh/m^2/year and 39.5 kWh/m^2/year respectively. This variation in operational patterns leads to nearly 40% variation in LCE between high and low consumption clusters. Embodied energy of the enclave is 3.16 X10^3 MJ/m^2. It varies from 400 X10^3 MJ/house to 570.3 x10^3 MJ/house based on the floor area. Considering a service-life of 50 years, the LCE is 1688.4 x10^3 MJ per residential unit. Operational energy share in the LCE for this service life period is 63%. The operational energy consumption pattern significantly affected the share of embodied energy and operational energy in LCE. For instance, the share of embodied energy varies from 42% for a low consumption cluster to 28% for a high consumption cluster.

9. References

Annual Report on the working of state power utilities and electricity departments. (2014). *Power and Energy division, Planning Commission, Government of India*.

Bureau of Energy Efficiency. (2014). Design guidelines for energy-efficient multi-storey residential buildings (Composite and Hot-Dry climates). New Delhi.

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, *29*, 394-416.

Chappells, H., & Shove, E. (2005). Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment. *Building Research & Information*, *33*(1), 32-40.

Devi, P., & Palaniappan, S. (2014). A case study on life cycle energy use of residential building in Southern India. *Energy and Buildings*, *80*, 247-259.

Dixit, M. K., Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, *42*(8), 1238-1247.

Erlandsson, M., & Borg, M. (2003). Generic LCA-methodology applicable for buildings, constructions and operation services—today practice and development needs. *Building and environment*, *38*(7), 919-938.

Hemsath, T. L., & Bandhosseini, K. A. (2015). Sensitivity analysis evaluating basic building geometry's effect on energy use. *Renewable Energy*, *76*, 526-538.

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings—A review of current trends. *Energy and Buildings*, *66*, 232-245.

ICE (2017) Embodied energy and carbon - The ICE database, http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html#.WHMVwYVOIjY, last retrieved 9th January, 2017.

Ioannou, A., & Itard, L. C. M. (2015). Energy performance and comfort in residential buildings: Sensitivity for building parameters and occupancy. *Energy and Buildings*, *92*, 216-233.

Praseeda, K. I., Mani, M., & Reddy, B. V. (2014). Assessing impact of material transition and thermal comfort models on embodied and operational energy in vernacular dwellings (India). *Energy Procedia*, *54*, 342-351.

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings*, *42*(10), 1592-1600.

Rajasekar, E., & Ramachandraiah, A. (2010). Adaptive comfort and thermal expectations–a subjective evaluation in hot humid climate. *Proceedings of the adapting to change: new thinking on comfort. Windsor, London, UK*, 9-11.

Thormark, C. (2002). A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. *Building and environment*, *37*(4), 429-435.

TV, Rijil Das., & Rajasekar, E. (2014). Effect of location specific climatic diversities on comfort and energy consumption: A study on India's composite climate zone. *Proceedings of counting the cost of comfort in a changing world. Windsor, London, UK*, 9-11.

Wang, L., & Greenberg, S. (2015). Window operation and impacts on building energy consumption. *Energy and Buildings*, *92*, 313-321.

Yohanis, Y. G., & Norton, B. (2002). Life-cycle operational and embodied energy for a generic single-storey office building in the UK. *Energy*, *27*(1), 77-92.

Yang, L., Yan, H., & Lam, J. C. (2014). Thermal comfort and building energy consumption implications–a review. *Applied Energy*, *115*, 164-173.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Method to determine Indoors Thermal Comfort Range for Mexico's climates

Luis Armando Canul-Euán[1], Luis Gabriel Gómez-Azpeitia[2] and Gonzalo Bojórquez-Morales[3]

[1] Faculty of Architecture and Design, Universidad de Colima, Coquimatlán, Colima, Mexico; lar.canul.e@gmail.com
[2] Faculty of Electronic Instrumentation and Atmospheric Sciences, Universidad Veracruzana, Xalapa, Vereacruz, Mexico; ggomez@ucol.mx
[3] Faculty of Architecture and Design, Universidad Autónoma de Baja California. Mexicali, Baja California, Mexico; gonzalobojorquez@uabc.edu.mx

Abstract: The research sought to establish a method to define a thermal comfort range standard correlating the thermal comfort range of different studies with adaptive approach carried out in interior spaces with the external thermal oscillation. The value of the coefficient of determination (R^2) was the validation parameter. The sample size was 38 studies conducted in Mexico, with 6,744 surveys. The methodology is based on a proposal made by Humphreys, Nicol and Roaf: for each day survey, subtract from the operating temperature (Top) its mean value to form the variable (δTop) and from the thermal sensation (ts) its mean value to form the variable δts. Next, a polynomial regression analysis of δts in δTop was performed to obtain an adjusted regression coefficient. The thermal comfort range per study was obtained from the inverse of the regression coefficient. Additionally, two alternative values of the regression coefficient were calculated: through the quotient of the standard deviations of the δtf and δTop, and of the quotient of the δts and δTop ranges. The results indicate a greater correlation between the OSC_δDBText and the comfort range of the inverse of the standard deviations. The value of R^2 was 0.4408.

Keywords: Thermal comfort, adaptive approach, comfort range, coefficient of determination

1. Introduction

The definition of the range of environmental conditions in which people express feeling thermally comfortable, can allow an efficient use of energy consumption, while optimizing health and productivity conditions. According to Gómez-Azpeitia (2007), the determination of a comfort range of temperatures in which people indicate to be comfortable with respect to the conditions of the space where they are located, is one of the pending tasks in thermal comfort studies in Mexico.

This comfort range is usually calculated from the neutrality temperature (Tn) and its limits have been established in different ways. The recurring method for its determination are the thermal comfort standards, such as ANSI-ASHRAE and the European standard EN 15251. The application of such standards has proved not to be suitable to all climatic conditions, since in many occasions it overestimates or underestimates the adaptive capacity of people. As a counterpart to this situation, several researchers are conducting field studies on thermal comfort with the main premise of establishing temperatures and comfort ranges locally or failing at a regional level (Chyee Toe et al, 2013; Djamila et al 2014; Figueroa et al, 2014; Zhang et al, 2011; Manu et al, 2016). However, the definition of the thermal comfort range follows the guidelines of the standards criteria, which do not reliably reflect what happens in the localities.

The thermal comfort range (TCR) varies, among other factors, depending on the circumstances of the climate and the characteristics of the people, so it is necessary to establish specific values for each type of population, social conditions, habits and climate. Know the neutral temperature and the thermal comfort ranges allows the development of tools and useful information for planning the design of homes, offices, among other spaces that help promote the thermal comfort of users (Bojórquez et al, 2010). However, such determination should not strictly follow the standards, because this could lead to homogeneous expectations of thermal environments regardless of geographical location, which negatively affect the comfort and health of people and increases the consumption of energy (Hitchings, 2009).

2. The use of Meta-analysis

The analysis of different databases of field studies on thermal comfort in different climatic zones and in different types of buildings can provide greater certainty in the temperatures and thermal comfort ranges. The conformation of several databases will allow the realization of a meta-analysis.

The results of the first meta-analysis with field studies carried out up to 1975 (Figure 1), found a correlation between the mean temperature of the interior and the neutral temperature (r=0.96). The neutral temperature range was 17°C to 33°C. (Humphreys et al, 2016).

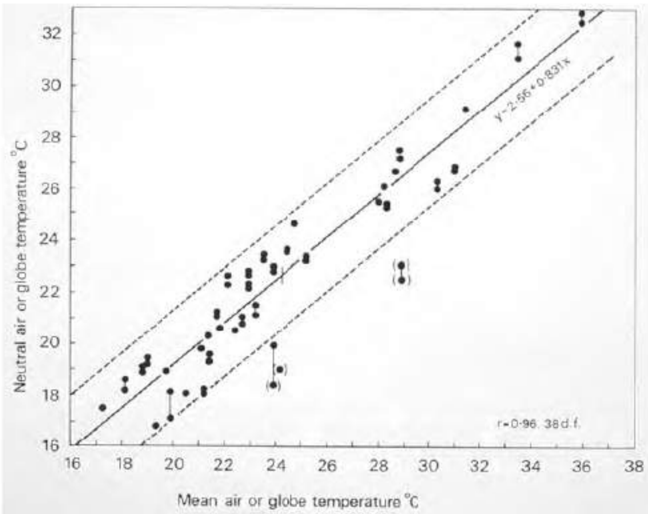


Figure 1. Correlation between the mean interior temperature and the neutral temperature (Humphreys et al, 2016)

A second analysis of the meta-base, found a strong correlation (r=0.97) between the mean monthly temperature outside and the neutral temperature. The variation of the comfort temperature was explained by 94% as a function of the outside temperature (Figure 2). The range comfort set was ± 2 ° C.

A third meta-analysis was conducted by de Dear et al (1997) with more than 21,000 surveys conducted in 160 buildings in 9 countries. The results differ from those found in the first meta-analysis. The correlation coefficient found in 1975 of 0.96, in the new data was 0.53, and therefore the value of R^2 fell from 0.92 to 0.28. The result of the third meta-analysis indicated a regression coefficient of 0.255, that is, for each increase of 4K in the mean outdoor temperature, the thermal neutrality is increased by 1K (Figure 3). The comfort range is determined at ± 3.5K and ± 2.5K for 80% and 90% acceptability, respectively.

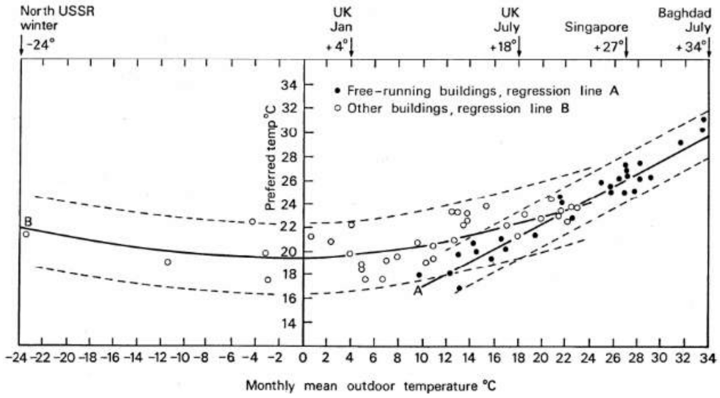


Figure 2. Correlation between the neutral temperatures against the mean monthly temperature of the exterior (Humphreys et al, 2016)

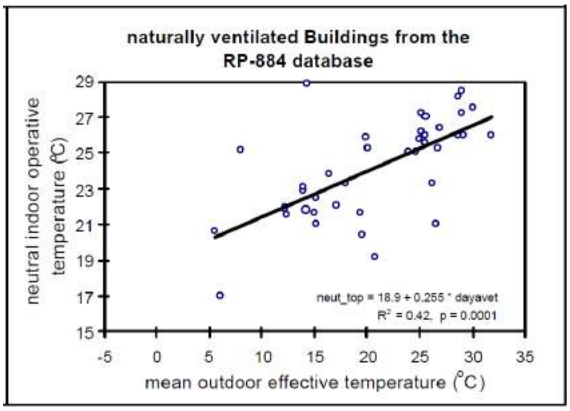


Figure 3. Dependence on the indoor neutrality of the external climate (de Dear et al, 1997)

By reproducing the method used by de Dear et al, the European Union (EU) developed the SCATs project that derived in the EN 15251 standard, collecting 4,655 cross-sectional surveys in five European cities. The comfort ranges are established according to three categories. The first was assigned a range of ± 2K, the second a value of ± 3K and the third of ± 4K.

3. Method

The application of surveys in field studies on thermal comfort has been the recurrent way for researchers to obtain information about the responses of thermal sensation that people experience. In addition to containing such responses, the surveys also collect information on the environmental data to which people are subject. The ANSI ASHRAE 55 standard and the European standard EN 15251 formed their databases using this practice. In order to determine the degree of relationship between the response given by people on a thermal sensation scale (TSS) and the dry bulb temperature (DBT), many of the field studies have made use of linear regression analysis for a single study or for a compendium of them. In thermal comfort studies, this statistical method examines the tendency of the mean thermal sensation response as a function of the recorded temperature. The graphic result of this relationship is a linear equation that predicts the behavior of the first variable.

Nowadays, the most practical way to obtain the value for the range of thermal confort in comfort studies is using some of the comfort models indicated in the established standards. A second option is the realization of field studies, through the application of surveys and monitoring of various variables. However, both paths involve some setbacks. The use of standards could underestimate or overestimate the adaptive capacity of people. The field studies necessarily involve the formation of a human work team as well as the use of sophisticated equipment, which has a high acquisition cost and is not always available.

The objective of the study was to establish a method to determine the range of thermal comfort applicable to interior spaces without artificial air conditioning for the representative climates of Mexico, based on field studies with an adaptive approach already carried out, relating them to their external thermal oscillation. Figure 4 indicates the steps in sequential form of the applied method.

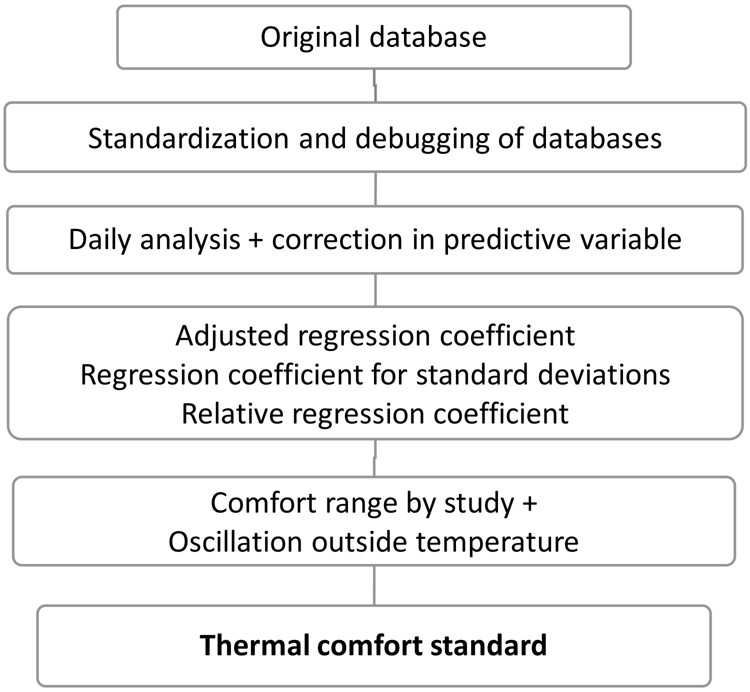


Figure 4. Steps of the method

3.1. Field studies collection

In a first stage, a meta-database was formed with different field studies on thermal comfort according to the classification made by Dear and Brager (1998). These studies were conducted in Mexico by different researchers in spaces without mechanical climate control to cool or heat, that is, ventilated naturally. Researchers was invited to collaborate in the creation of a national meta-database, requesting their raw databases.The first studies on thermal comfort in Mexico were conducted in 2006. The information collected in the field studies was grouped into four groups (Morgan Torres, 2017):

- Design of the field study: an analysis was carried out to determine the city, the climate, the climatic seasons and the population to be studied.
- Evaluation of the perception of the environment: this was done with the support of surveys designed in accordance with the standards ISO 10551: 2005 and ANSI / AHSRAE-55. Additionally, personal data were recorded such as sex, age, height, weight, metabolic rate, type of clothing.
- Measurement of environmental variables: measured and recorded simultaneously with the application of the survey. The equipment and instruments used are in accordance with the specifications of ISO 7726: 1998.
- Information capture: the process of digital capture of the information collected in the surveys was carried out by pairs of people with the intention of detecting errors during the collection of data and their capture in the database.

Table 1 groups the 38 field studies carried out that make up the metabase of data according to the climate of place. The place and year where the study was conducted, the original number of surveys collected and the total number of climate surveys are indicated. Five types of climate were identified: warm sub-humid (WSH), warm wet (WW), semi-cold (SC), warm dry (WD) and temperate sub-humid (TSH). Figure 5 shows the geographical location of each of the studies. The studies in each of the cities were conducted by climatic seasons, this allowed to consider each season as a study in the metabase.

Table 1. List of field studies conducted in Mexico

No. of study	Climate	Place	Original surveys	Total
1	Warm-subhumid (WSH)	Colima (2006-2007)	203	
2			203	
3			202	
4		Culiacán (2008)	151	
5		Chiapas (2009-2010)	128	
6			64	
7			120	
8		Manzanillo (2014)	166	
9			337	
10		Culiacán (2016)	236	
11			469	2279
12	Warm-wet (WW)	Mérida (2007)	150	
13		Mérida (2016)	1017	
14			709	
15		Mérida (2016)	325	2201
16	Semi-cold (SC)	Pachuca (2013-2014)	325	
17			409	
18			425	
19			397	1556
20	Warm-dry (WD)	Hermosillo (2006-2007)	145	
21			150	
22		Mexicali (2006-2007)	80	
23			49	
24			15	
25			91	
26		La Paz (2007-2008)	125	
27			59	
28		Chihuahua (2010)	146	
29			123	
30		Cd. Juárez (2010)	126	
31			136	
32		Chihuahua (2016)	217	
33		Mexicali (2015)	168	
34		Mexicali (2016)	46	1676
35	Tempered sub-humid (TSH)	Zona Metropolitana del Valle de México (2013-2014)	72	
36			97	
37			93	
38			129	391
		Total	**8,103**	**8103**

Figure 5. Geographical location of the field studies that made up the meta-database

From the data of dry bulb temperature (DBT), globe temperature (TG) and relative humidity (RH), were calculated for the interior, the mean radiant temperature (MRT), operating temperature (Top) and corrected effective temperature (CET). For the exterior values of the wet bulb temperature (WBT) and external CET were calculated, based on the known data of DBT and RH. If a field study did not have the record of the weather variables from outside, the data was obtained using the METEONORM program.

3.2. Standardization and debugging of databases

According to the objectives of each study, the criteria and values used by each researcher were different, therefore, they had to be homologated. Table 2 presents a summary of the standardization of the database. For example, for the thermal sensation vote category, some researchers used the Bedford´s scale that assigns the neutrality vote a value of four instead of zero as indicated on the ASHRAE scale. The standardization of the meta-database used the scale of the ASHRAE standard.

Based on the meta-database, the surveys of each study were refined according to the following criteria:

- Buildings where the HVAC systems was on.
- The respondent indicated intense activity at the time of the survey.
- The respondent stayed less than 15 minutes inside the room.
- The values of the TG were greater than 10 ° C with respect to the DBT.
- Consider persons interviewed under 12 years of age or over 65 years of age.

If any survey had the presence of any of these criteria, it was not considered in the statistical analysis. Possible errors such as the poor accuracy of the instruments, their position with respect to the people at the time of conducting the surveys, as well as the proximity of the instruments with other bodies, were solved with the statistical procedure based on the error of the variance.

Table 2. Studies that make up the meta-database

Criteria	Classification
Control devices	1. Everything closed
	2. Open doors and windows
	3. Curtains
	4. Fans
Time inside the room	1. Less than 15 min
	2. more than 15 min
Sex	1. Man
	2. Woman
Type of chlothing	1. Light: short-sleeved shirt and shorts
	2. Normal: short sleeve shirt and trousers
	3. Formal suit: long sleeve shirt, trousers and jacket
	4. Winter clothing: sweater, jacket, trousers
	5. Arctic clothing: thick sweater, coat and trousers
Thermal sensation	+3 Hot
	+2 Warm
	+1 Slightly warm
	0 Neutral
	-1 Slightly cool
	-2 Cool
	-3 Cold
Thermal acceptance	1. Generally acceptable
	2. Generally unacceptable
Thermal preference	+3 Much more heat
	+2 More heat
	+1 A Little more heat
	0 Unchanged
	-1 A Little more cold
	-2 Colder
	-3 Much more cooler
Ventilation preference	+3 Much more wind
	+2 more wind
	+1 A Little more wind
	0 Unchanged
	-1 A Little more wind
	-2 More wind
	-3 Much more wind

3.3. Analysis per day of surveys and correction in the predictor variable

By convention, the pair of data located in a scatter diagram corresponds to the responses of thermal sensation (vertical axis) and to the records of temperature of the environment (horizontal axis) obtained during the study. Some researches relate the totality of the pair of data in a single diagram; some others design from the beginning, the differentiation by zones and/or climatic seasons (Indraganti et al, 2014, Rincón Martínez, 2015, Gómez-Azpeitia et al, 2007). However, in either case, the evaluation for long periods (monthly, annual) overestimates the sensitivity of people to their thermal environment and dilutes the effects of daily variations in temperature due to the process of adaptation of the people.

To avoid such inconvenience, the methodology proposed by Humphreys et al (2016) was used, which takes as the unit of analysis the information collected in a single day, due to the fact that better reflect sensitivity to change of daily temperature that people experience. The method indicates that for each day survey, subtract from the TG its mean value to form the variable δtg and from the thermal sensation (ts) its mean to form the variable δts. However, for this investigation the operating temperature (Top) was used as a variable of the environment. With these values (δTop and δts), regression analysis was used to obtain a weighted value and increase the accuracy of the regression coefficient. This method is only applicable to cross-sectional studies. Table 1 shows the scale of thermal sensation used in accordance with the ANSI-ASHRAE-2013 standard indicating values in a range of ± 3.

Additionally, a statistical procedure based on error variance was applied to adjust the regression coefficient resulting from the ratio of δTop and δts, due to the possible presence of measurement errors in the values of temperatura (Humphreys et al, 2016). Such errors are a result of measurements of environmental variables in places close to the location of the respondent instead of where is the person, and would affect both the regression coefficient by skewing it down, as well as the value of the correlation coefficient (r) and therefore also the value of the coefficient of determination (R^2).

To obtain the estimate of the adjusted regression coefficient (b_{adj}), without the presence of the error in the predictor variable is used the equation 1, which allows crediting the sensitivity in the estimation of the regression coefficient for an estimated value of their error, and adjusting it accordingly.

$$b_{adj} = b_{err}(\sigma^2_{Top})/\left(\sigma^2_{Top}\right) - (\sigma^2_{err}) \qquad \textit{Ec (1)}$$

b_{adj} = adjusted regression coefficient
b_{err} = adjusted regression coefficient after the regression of δtf in δTop
σ^2_{Top} = variance of the operating temperature
σ^2_{err} = error variance.

3.4. Thermal comfort range by study

The range of comfort by study was a result of the reciprocal of the value of the regression coefficient (1/G). The relationship determines the range of temperature between the intersections of the regression line with the orderly -1 and the orderly +1 of the votes of thermal sensation (VTS). The regression coefficient was calculated in three different ways: the first value corresponds to the adjusted coefficient (b_{adj}); a second procedure consists in the relation between the standard deviations (σ) of the VTS and Top as shown in equation 2. The third procedure to obtain the value of G is called the relative coefficient (b_{rel}) proposed by Gómez-Azpeitia (2016), which indicates that knowing the maximum and minimum values of the VTS and the Top, the value of the regression coefficient is the ratio of their ranges as shown in equation 3. For the three procedures, the values used were those of δts and δTop.

$$G = \frac{\sigma\ \delta ts}{\sigma\ \delta Top} \qquad \textit{Ec (2)} \qquad\qquad G = \frac{Range\ \delta ts}{Range\ \delta T_{op}} \qquad \textit{Ec (3)}$$

3.5. Thermal comfort standard

Obtained the ranges of confort by study, these were correlated with the oscillation of the outdoor temperatures ($OSC\_\delta DBT_{ext}$) recorded in each study in a scatter diagram, which are to be used in the construction of a standard of termal comfort for Mexico. The OSC_δDBText was obtained from the subtraction between the maximum and the minimum outside temperature recorded during the total days of the study. To obtain the values of the exterior temperature was as follow: at each outside temperatura, the mean value was subtracted to obtain δDBT_{ext}.

4. Results

4.1. Conformation of the meta-database

The total number of studies conducted was thirty-eight conducted in 12 cities in Mexico, with 8,103 surveys collected in 353 days. The studies were conducted between 2006 and 2017, mostly in warm weather during the summer and winter. Bach to the debugging (Morgan Torres, 2017), the number of surveys considered for analysis was 6,744 in 323 days, representing 83% of the total original surveys. Thirty studies were conducted in homes, six in school classrooms and two in the waiting room of a hospital. Table 3 indicates for each study the number of surveys collected and the number of surveys considered after debugging. The software used for the analysis of the meta-database was Microsoft Excel®.

Table 3. Database that make up the meta-base

No. of study	Climate	Original surveys	Survey used	No. of study	Climate	Original surveys	Survey used
1	Warm-subhumid (WSH)	203	185	20	Warm-dry (WD)	145	77
2		203	186	21		150	140
3		202	172	22		80	65
4		151	116	23		49	41
5		128	125	24		15	12
6		64	55	25		91	47
7		120	92	26		125	105
8		166	159	27		59	44
9		337	321	28		146	124
10		236	14	29		123	104
11		469	34	30		126	110
12	Warm-wet (WW)	150	126	31		136	117
13		1017	1017	32		217	148
14		709	709	33		168	145
15		325	305	34		46	41
16	Semi-cold (SC)	325	295	35	Tempered sub-humid (TSH)	72	64
17		409	402	36		97	92
18		425	400	37		93	88
19		397	363	38		129	104
					Total	**8103**	**6744**

Organizing the studies by climate, allowed to perform a frequency analysis of the thermal sensation responses for each of the five climates where studies were carried out (Table 4). For all climates, a greater number of VTS is observed in the neutral category. If the total of the VTS is considered, this category represents 39.5%. Taking as a reference the range of ± 1 considered as comfort, the number of answers is 4,925, which represents 73% of the total. The votes of feeling too cold are minimal (0.56%), it is attributed to the fact that most of the studies were carried out in hot climates. On the contrary, the votes of feeling too hot represent little less than 10% of the total.

Table 4. VTS Frequency by type of climate

	Type of climate					
VST	WSH	WW	SC	WD	TSH	Total VST
3	191	325	3	119	14	652
2	284	389	44	172	23	912
1	358	522	250	199	35	1364
0	509	664	699	623	173	2668
-1	94	223	378	128	70	893
-2	22	25	85	52	33	217
-3	1	9	1	27	0	38
Total by climate	**1459**	**2157**	**1460**	**1320**	**348**	**6744**

Figures 6, 7 8, 9 y 10 shows the frequency histogram of the VTS collected in each of the climates, as well as the scatter diagram between Top and st. It is observed that for the hot climates, the concentration of the VTS, is on the heat side in the ts scale (Figures 6, 7 and 9). Such concentration is most noticeable in the WW climate, where 325 people (15%) responded feeling too hot and only nine people (0.40%) said they felt too cold. As expected, in the SC and TSH climates the responses are on the cold side of the st scale (Figures 8 and 10). The scatter diagrams indicate the resulting equation and the R^2 value of the correlation between Top and st. The maximum-minimum Top (°C) range for climates were as follows: WSH, 39.14-18.27°C; WW, 46.24-25.63°C; SC, 28.93-14.10°C; WD, 44.69-12.30°C and TSH, 30.0-9.29°C.

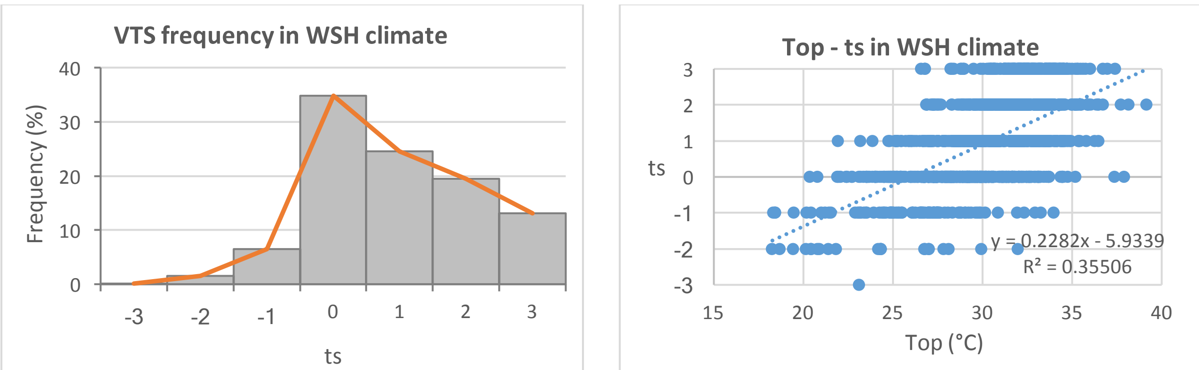


Figure 6. Histogram and scatter diagram in WSH climate

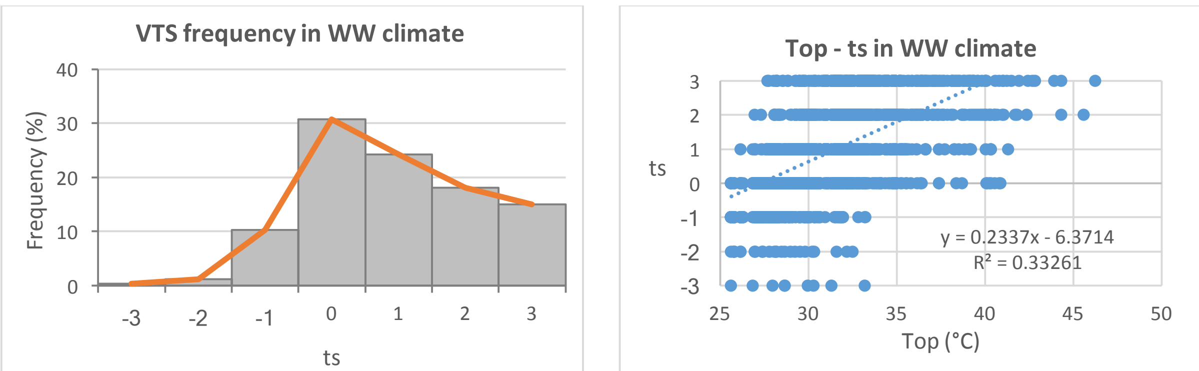


Figure 7. Histogram and scatter diagram in WW climate

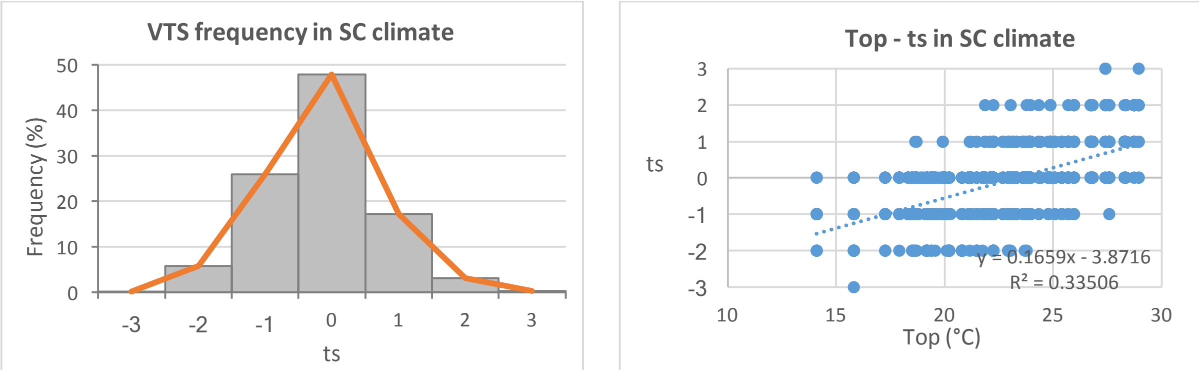


Figure 8. Histogram and scatter diagram in SC climate

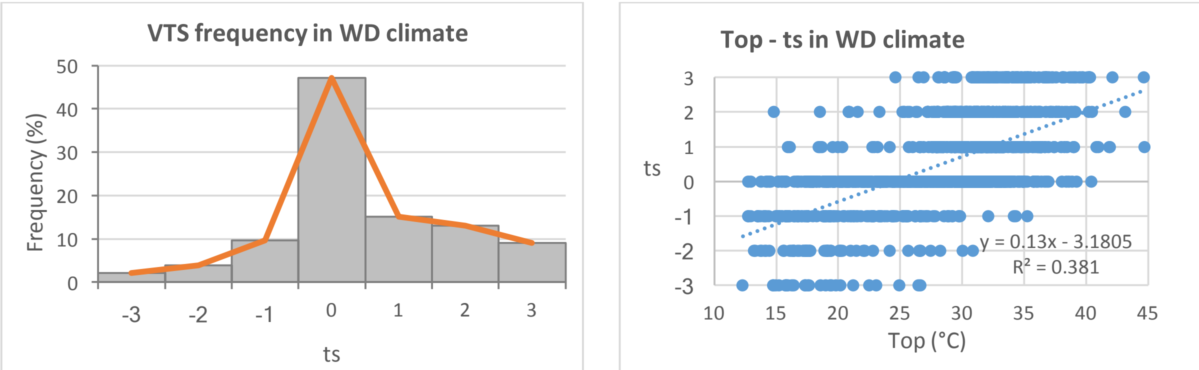


Figure 9. Histogram and scatter diagram WD climate

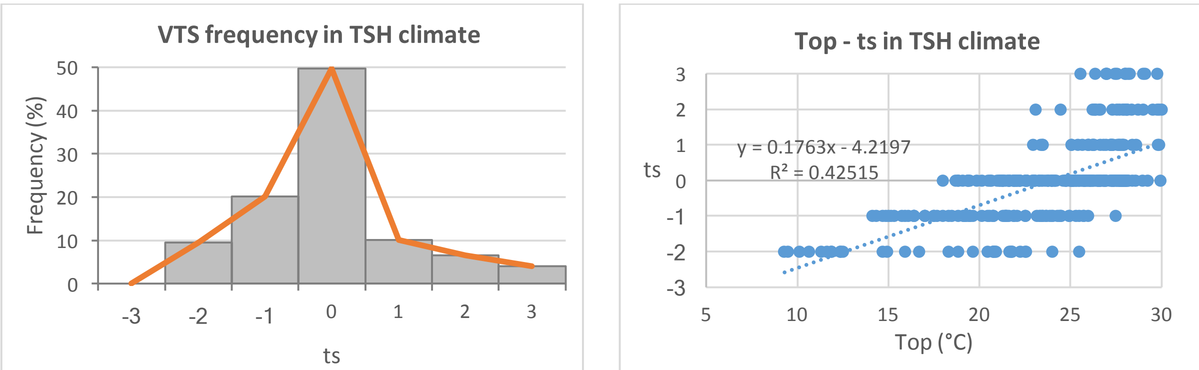


Figure 10. Histogram and scatter diagram TSH climate

Figure 11 shows the frequency graph for the 6,744 wind chill votes. A greater frequency is observed in the votes of neutrality, which decreases as it moves away from this category.

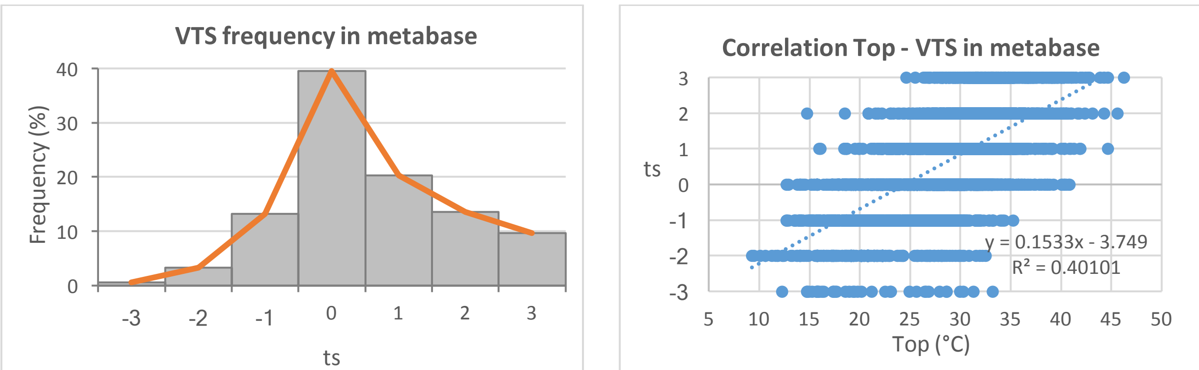


Figure 11. Histogram and scatter diagram in metabase

Within each study, the means of the VTS, the Top and the DBT exterior were calculated. Figure 12 graphs the relationship between the mean Top and the mean DBT_{ext} of the 38 studies. A strong correlation (r = 0.87) is observed between the pair of plotted data. The variation of the Top is explained in 76% a function of the external dry bulb temperature.

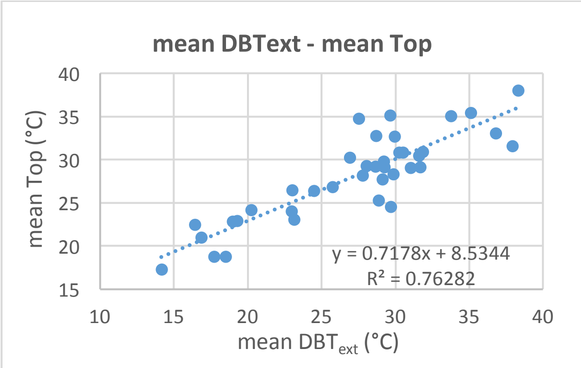
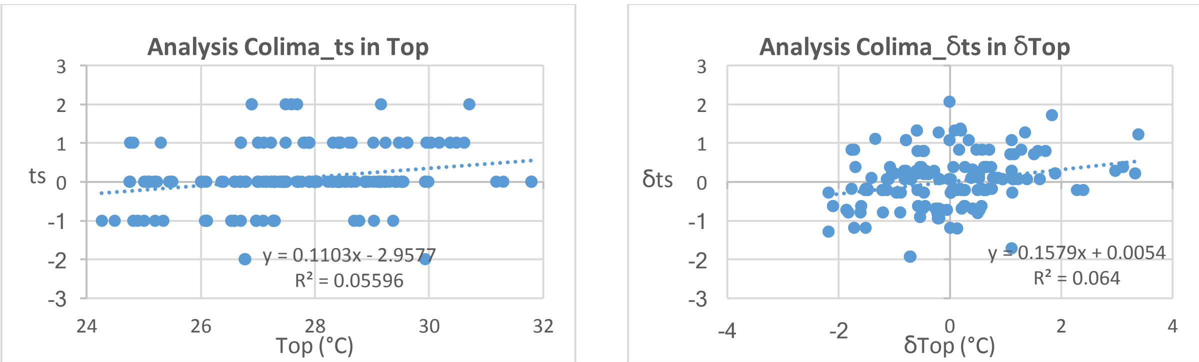


Figure 12. Relationship between mean indoor Top and mean DBText

4.2. Dayli analisis

For each of the 38 databases, was conducted a conventional linear regression analysis that relates the responses of thermal sensation and the value of the operating temperature. Subsequently, the method of daily analysis was applied to visualize the differences relating the data pair of δTop and δts. Figure 13a shows the scatter diagram of the surveys of study 2 with a conventional analysis. The analysis of the same surveys in days grouped is shown in figure 13b.

An increase in the value of the regression coefficient is observed, as well as the value of R^2 when the analysis is made per day. The dispersion of the points with respect to the trend line is reduced in a daily analysis.



a) b)

Figure 13. Scatter diagram between the operative temperature as a function of the thermal sensation

Table 5 shows the values of the regression coefficients for the days grouped and their corresponding adjusted coefficients, as well as other statistical values obtained for each of the databases. The value of 0.158, attributable to the error of variance due to the position of the thermometer, was defined as indicated by Humphreys et al (2016). The value for the adjusted regression coefficient was determined according to equation 1.

For all studies, the value of the adjusted regression coefficient increased. However, except for study 17, the rest of them indicate a discrete and even minimal improvement with regard to the analysis per day. The improvement was in the range of 2 to 32%.

With the application of the method of daily analysis for naturally ventilated buildings, Humphreys et al (2016), reported an increase in the adjusted regression coefficient of 0.097 for the base of the SCAT's project, going from 0.361 to 0.458; using the meta-base of ASHRAE indicate an increase of 0.124 from 0.308 to 0.432. The overall improvement for this investigation was only 0.024, the result of subtracting the average value of the regression coefficient per day from the adjusted regression coefficient.

Table 5. Values of the regression coefficients (days grouped) and adjusted coefficients from the meta-base

No. of study	No. of observations	Variance of δTop	Estimate of error variance in δTop	Regression coefficient	s.e. of coefficient	Adjusted regression coefficient
1	185	2.18	0.158	0.181	0.040	0.1954
2	186	1.14	0.158	0.158	0.045	0.1833
3	172	1.74	0.158	0.307	0.049	0.3373
4	116	4.19	0.158	0.103	0.040	0.1075
5	125	1.89	0.158	0.235	0.049	0.2566
6	55	0.65	0.158	0.287	0.142	0.3790
7	92	2.35	0.158	0.361	0.053	0.3874
8	159	1.25	0.158	0.185	0.074	0.2115
9	321	2.82	0.158	0.155	0.032	0.1644
10	14	0.92	0.158	0.266	0.123	0.3216
11	34	6.03	0.158	0.259	0.057	0.2661
12	126	1.08	0.158	0.175	0.075	0.2053
13	1017	2.45	0.158	0.225	0.020	0.2401
14	709	1.51	0.158	0.195	0.028	0.2174
15	305	7.90	0.158	0.029	0.019	0.0293
16	295	4.19	0.158	0.179	0.018	0.1861
17	402	0.25	0.158	0.186	0.076	0.4985
18	400	0.99	0.158	0.122	0.034	0.1452
19	363	2.12	0.158	0.178	0.021	0.1927
20	77	3.06	0.158	0.119	0.054	0.1256
21	140	1.23	0.158	0.089	0.054	0.1020
22	65	2.65	0.158	0.084	0.059	0.0894
23	41	2.94	0.158	0.057	0.082	0.0601
24	12	5.72	0.158	0.059	0.130	0.0606
25	47	5.32	0.158	0.208	0.058	0.2139
26	105	3.08	0.158	0.153	0.057	0.1609
27	44	1.56	0.158	0.405	0.086	0.4501
28	124	4.40	0.158	0.082	0.041	0.0855
29	104	3.64	0.158	0.208	0.046	0.2172
30	110	3.22	0.158	0.125	0.056	0.1315
31	117	4.12	0.158	0.089	0.047	0.0929
32	148	4.80	0.158	0.084	0.031	0.0867
33	145	5.83	0.158	0.072	0.025	0.0739
34	41	6.47	0.158	0.341	0.060	0.3492
35	64	4.78	0.158	0.202	0.048	0.2084
36	92	2.07	0.158	0.113	0.037	0.1219
37	88	3.31	0.158	0.197	0.056	0.2073
38	104	2.02	0.158	0.150	0.058	0.1631
	6744			**0.1743**	**0.0548**	**0.1980**

4.3. Relating the external oscilation with the comfort range

As indicated in section 3.4, the regression coefficients were calculated in three different ways for each of the study databases: the adjusted coefficient, the gradient of the deviations, and the relative gradient. Next, three different comfort ranges were obtained for each database. Table 6 indicates the values of the ranges of comfort obtained from the reciprocal of the gradient value (1/G), as well as the oscillations of the outside temperature ($OSC\_\delta DBT_{ext}$).

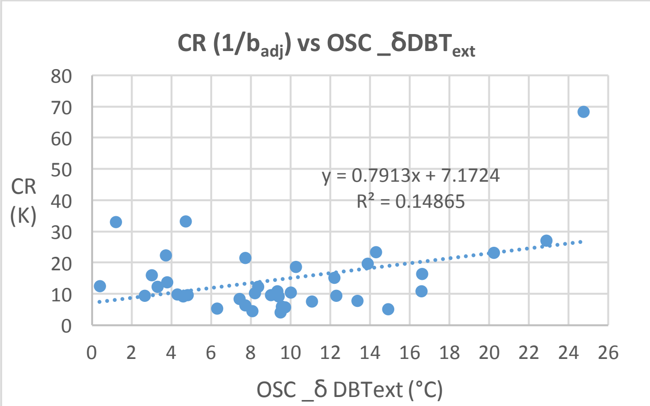
Table 6. Thermal comfort range values of the meta-base

No. of study	CR ($1/b_{adj}$)	CR ($1/b\sigma$)	CR ($1/b_{rel}$)	$OSC\_\delta DBT_{ext}$	No. of study	CR ($1/b_{adj}$)	CR ($1/b\sigma$)	CR ($1/b_{rel}$)	$OSC\_\delta DBT_{ext}$
1	10.23	3.50	3.51	8.20	20	15.93	4.12	5.72	3.00
2	10.91	3.20	2.78	9.34	21	19.61	3.10	3.01	13.86
3	5.93	2.80	2.87	9.55	22	22.37	4.20	4.25	3.70
4	18.60	4.52	3.12	10.26	23	33.27	3.89	3.65	4.70
5	7.79	3.37	3.11	13.36	24	33.01	4.82	4.91	1.20
6	5.28	1.87	1.96	6.30	25	9.35	4.55	7.18	12.30
7	5.16	3.23	4.61	14.90	26	12.43	3.36	4.35	0.38
8	9.46	2.10	3.69	2.65	27	4.44	2.91	3.36	8.07
9	12.16	3.35	4.88	3.30	28	23.40	4.34	3.62	14.30
10	9.20	2.56	1.69	4.59	29	9.21	3.90	5.25	9.40
11	6.22	3.98	5.36	7.70	30	15.21	3.33	3.32	12.20
12	9.74	2.33	2.61	4.28	31	21.54	3.89	4.54	7.72
13	8.33	2.96	2.24	7.42	32	23.07	5.24	4.53	20.22
14	9.20	2.56	1.69	4.59	33	27.06	6.55	4.99	22.89
15	68.37	6.04	8.25	24.73	34	5.73	3.94	4.44	9.71
16	10.75	5.54	3.85	16.57	35	9.60	4.69	5.45	4.80
17	4.01	1.31	1.66	9.50	36	16.40	5.40	5.12	16.60
18	13.77	2.89	2.05	3.77	37	9.65	3.62	3.38	9.00
19	10.38	4.64	3.34	10.00	38	12.26	3.33	4.59	8.34

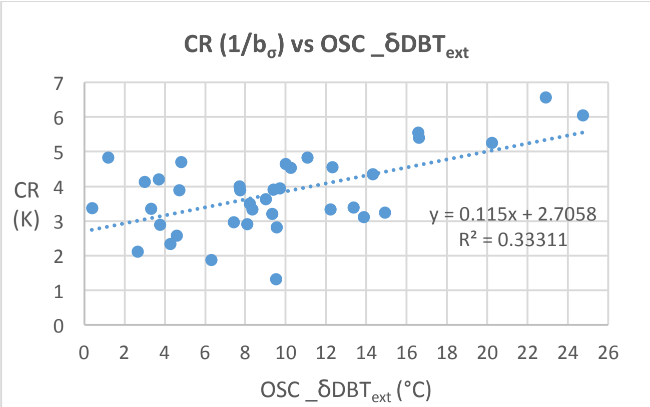
When the comfort range (CR) was calculated using the value of the adjusted regression coefficient, their values are inadmissible and impractical. Many of the values are higher than 10 K, at 20 K, at 30 K and even, a CR of 68.37 K (±34.18 K) was obtained. With the use of the coefficients from the ratios of the standard deviations of δtf and δTop or of the δft and δTop ranges, the CR are more congruent. The values vary from 1.31 K (± 0.66 K) to 6.55 K (± 3.27 K) and of 1.66 K (± 34.18 K) to 8.25 K (± 4.12 K) respectively.

The graph of the linear correlation between the three ways to obtain the CR and the $OSC\_\delta DBT_{ext}$ are shown in figure 14. To relate the values of the exterior with the CR from the adjusted coefficient, a slope of the line close to 0.80 is obtained, with a value of R^2 of 0.15 (Figure 14a). The figure clearly shows the distance of a point corresponding to a day of survey. If this day survey was not considered, the values for the slope of the line and R^2 were 0.11 and 0.006 respectively.

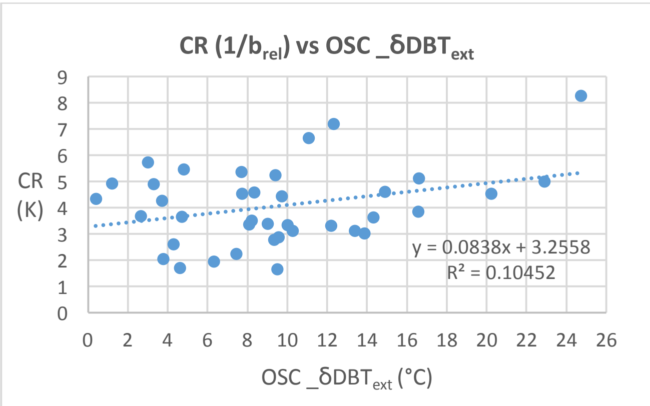
When the graphical analysis was made with the CR from the coefficient of the deviations, although a greater concentration of the points to the regression line is observed, the latter registered a value of 0.115 for its slope, but its value of R^2 now it was 0.333 (figure 14b). Finally, the analysis of the relative comfort range with the external temperature records indicated a slope of the regression line of 0.084 and a value of R^2 of 0.104 (Figure 14c). The minimum and maximum oscillation of the outside temperature for the studies was 0.38 and 24.73 respectively.



a)



b)



c)

Figure 14. Scatter diagram for comfort ranges as a function of the average outside temperature

According to Bojórquez Morales (2010), a value of R^2 less than 0.50 indicates a low correlation with a dispersed sample. The three analyzes obtained a R^2 below this value. With the intention of increasing it, an analysis was performed with a polynomial function of order 2, to the correlation between the CR from the standard deviations and the $OSC\_\delta DBT_{ext}$, having been this, the analysis that obtained the highest value of R^2 in the lineal funtion.

Figure 15 shows the scatter diagram of the correlation of the two variables. Now the value of R^2 is 0.4408, which reflects an increase of 0.1077 compared to the analysis of data with a lineal function.

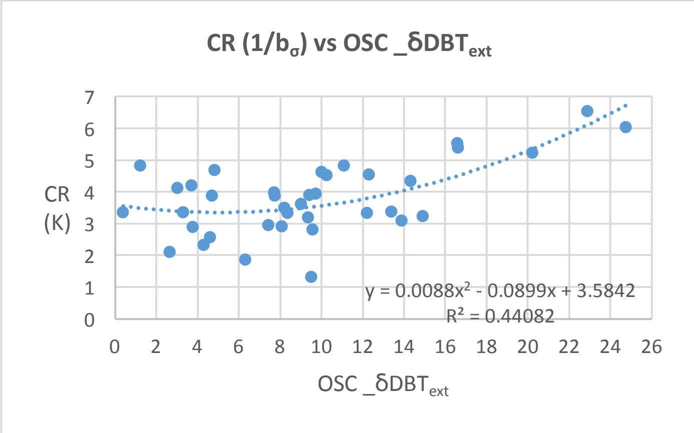


Figure 15. Polynomial dispersion diagram for the comfort range that was obtained from the standard deviation, based on the average temperature of the exterior

The value of R^2 in a polynomial function when the CR was related from the adjusted regression coefficient with the oscillation of the outside temperature was 0.58. In spite of a higher value compared to the previous analysis, the scatter of the points of the line, a low value of R^2, as well as very high comfort ranges in several of the 38 studies in the lineal analysis, make this correlation less reliable. The polynomial analysis between the CR obtained from the relative coefficient and the oscillation of the outside temperature indicates a value of R^2 of 0.23.

5. Conclusions

The study attempted to establish a methodological process to define a standard range of thermal comfort for interior spaces that function without mechanical cooling or heating systems correlating the oscillation of the outside temperature with the ranges of comfort of 38 studies already carried out. The databases were analyzed by day survey and applied a statistical process of correction in the predictor variable. Three procedures were determined to obtain the range of comfort.

It is concluded that the correlation between the range of thermal comfort obtained from the standard deviations and the oscillation of the outside temperature, has the best statistical conditions to be considered the basis in the development of a standard range of thermal comfort for Mexico. The development of field studies on thermal comfort continues to be carried out in the country, so that at some time, the metabase so far formed will have ample possibilities to increase and continue to work on your improvement.

It presents a model to set the local thermal comfort range by using the following equation:

$$RC = 0.0088\,(Osc\ ext^2) + 0.0899\,(Osc\ ext) + 3.5842$$

The value of 0.158 used to correct for the presence of variance error is only an estimate of the sensitivity of the regression coefficient that was obtained from the ASHRAE database, and therefore it is in a certain way, imprecise. In this regard, this research has found an average preliminary value of the 38 studies for this error variance of 0.10. However, due to its incipient determination, it is believed that the value of 0.158 is more reliable.

Acknowledgment

To the researchers of the field studies for having the availability of sharing their databases.

6. References

ANSI/ASHRAE55, 2004. *Thermal Environmental conditions for Human Occupancy.* s.l.:s.n.

Bojorquez, G., 2010. *Confort térmico en exteriores: actividades en espacios recreativos, en clima cálido seco extremo.* PhD. Universidad de Colima

Bojórquez, G. et al., 2010. Temperatura neutral y rangos de confort térmico para exteriores, período cálido en clima cálido seco. *Ambiente construído,* 10(2), pp. 133-146.

Chyee Toe, D. & Kubota, T., 2013. Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot–humid climates using ASHRAE RP-884 database. *Frontiers of Architectural Research,* Volume 2, pp. 278-291.

de Dear, R., Brager, G. & Cooper, D., 1997. *Developing an adaptive model of thermal comfort and preference. Final report ASHRAE RP-884,* s.l.: ASHRAE RP-884.

Djamila, H., Chu, C. & Kumaresan, S., 2014. Effect of Humidity on Thermal Comfort in the Humid Tropics. *Journal of Building Construction and Planning Research,* Volume 2, pp. 109-117.

Figueroa, C., Figueroa, A. & Bojórquez, G., 2014. Temperatura neutral y rangos de confort térmico en vivienda de producción en serie de la zona metropolitana del Valle de México, período frío. *XXXVIII Semana Nacional de Energía Solar XI Congreso Iberoamericano.*

Gómez-Azpeitia, G., 2016. *Método para determinar el coeficiente de regresión de Griffiths. Apuntes no publicados.* Colima(Colima): s.n.

Gómez-Azpeitia, G., Ruiz, R., Bojórquez, G. & Romero, R., 2007. *Monitoreo de condiciones de confort térmico: Reporte técnico (Producto 3),* Colima, Colima: s.n.

Hitchings, R., 2009. Studying thermal comfort in context. *Building Research & Information,* 37(1), pp. 89-94.

Humphreys, M., Nicol, F. & Roaf, S., 2016. *Adaptive Thermal Comfort: Foundations and Analysis.* USA: Routledge.

Indraganti, M., Ooka, R., Rijal, H. & Brager, G., 2014. Adaptive model of thermal comfort for offices in hot and humid climates of India. *Building and Environment,* Volume 74, pp. 39-53.

Manu, S. et al., 2016. Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). *Building and Environment,* Volume 98, pp. 55-70.

Morgan Torres, N., 2017. *Desarrollo de un estándar mexicano de confort térmico para edificios ventilados naturalmente.* Master. Universidad de Colima

Rincón Martínez, J. C., 2015. *Confort térmico en bioclima semi-frío: Estimación a partir de los enfoques de estudio adaptativo y predictivo.* PhD. Universidad Autónoma Metropolitana.

Zhang, H., Arens, E. & Pasut, W., 2011. Air temperature thresholds for indoor comfort and perceived air quality. *Building Research and Information,* 39(2), pp. 134-144.

The impact of the quality of homes on indoor climate and health: an analysis of data from the EU-SILC database

Ashok John[*1], Andreas Hermelink[2], Nicolas Galiotto[3], Peter Foldbjerg[3], Katrine Bjerre Milling Eriksen[3] and Jens Christoffersen[3]

[1] Ecofys Germany GmbH, Am Wassermann 36, 50829 Cologne, Germany
*Corresponding author: a.john@ecofys.com
[2] Ecofys Germany GmbH, Albrechtstr. 10c, 10117 Berlin, Germany
[3] VELUX A/S, Ådalsvej 9, 2970 Hørsholm, Denmark (Presenting author)

Abstract: Today one out of six Europeans (84 million Europeans, or the equivalent of Germany's population), report deficiencies regarding the building status. In some countries, that number is as high as one out of three. This puts these buildings in the 'Unhealthy Buildings' category, which is defined as buildings that have damp (leaking roof or damp floor, walls or foundation), a lack of daylight, inadequate heating during the winter or overheating problems. 10% of Europeans report having poor perceived general health. And the probability that a person reports poor health increase up to 70% if that person also lives in an unhealthy building vs. a healthy one. The results of this study show a correlation between poor health and the specific unhealthy building factors: • 1.7 times report poor health in a damp building; • 1.5 times report poor health when living in a building with insufficient daylight; • 1.3 times report poor health when perceiving overheating; • 1.7 times report poor health when living in uncomfortably cold temperatures. The paper is based on an analysis of the correlation between health and buildings in 27 EU member states using the Eurostat database EU-SILC (Survey on Income and Living Conditions). The presented research is based on EU-SILC raw data. For the purpose of the study, Eurostat approved the research proposal behind the analysis and gave access to the data to Ecofys Germany GmbH.

Keywords: Health, building, indoor climate, EU-SILC, European Union

1. Introduction

Around 508 million European citizens (EUROSTAT, 2015) spend about 90% of their time indoors (living and working) (NEST, 2004). Therefore Europe's buildings have a major impact on Europeans' health. According to WHO's definition (since 1948) "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity."

Yet, research assessing the statistical links between health and housing conditions is largely missing. Considering that building renovation is a huge intervention into the whole building system – cross-cutting technical aspects of the building itself and social as well as economic issues of the dwellers – it is necessary to fully grasp the implications, risks and chances. Therefore, a main research objective is to identify these links and to highlight which part of Europe's and MS's population is most in need of building renovation.

This insight triggered a detailed study on the relation between health and housing conditions across EU28 and its Member States. The results described here have been presented in the scientific report "The relation between quality of dwelling, socio-economic status and health in EU28 and its Member States" (Hermelink & John, 2017).

2. Methodology

The research is based on analysing Eurostat microdata from the EU-wide survey „Income and Living Conditions in Europe“.(EU-SILC). EU-SILC is a Eurostat Survey, which is conducted in a European-wide household panel, to assess the status and development of Income and Living Conditions in Europe. The EU SILC survey covers amongst others the domains housing including economic issues and health. Data in EU-SILC are collected either on household or individual level. For this research, anonymised results for more than 100,000 individual households and more than 250,000 adults (16 +) across all EU Member States – except Germany - were made available by Eurostat. The focus of this study lies on data from 2012, where more detailed information on housing conditions was collected. To handle the massive amount of data the statistical computing program R (version 3.3.0) was used for statistical analyses of the microdata.

3. Results

The research reveals that around 16% of Europeans report deficiencies regarding the building status; either because of dampness (leaking roof or damp floor, walls or foundation), lack of daylight, inadequate heating during the winter or overheating problems. The analysis also shows that around 44 Mio adults report poor perceived general health; this is equivalent to nearly 10% of the European population. As described above, the results will focus on the linkage between building status and health. Accordingly, the focal point of analysis described here are

- health in damp buildings.
- health in dark buildings.
- health in overheated buildings.
- health in building with uncomfortably cold temperatures

Detailed results of each of the mentioned topics will be described in the following subsections.

3.1. Health in damp buildings

15% of EU households (more than 30 Mio; or more than 60 Mio adults) report to live in damp buildings (leaking roof, damp floor/walls /roof/ foundation etc.).

- When adults report no dampness 9% report poor health
- When adults report dampness 16% report poor health

The probability that adults report poor health is significantly higher in homes with reported dampness; across the EU the probability is 1.7 times higher than with no dampness.

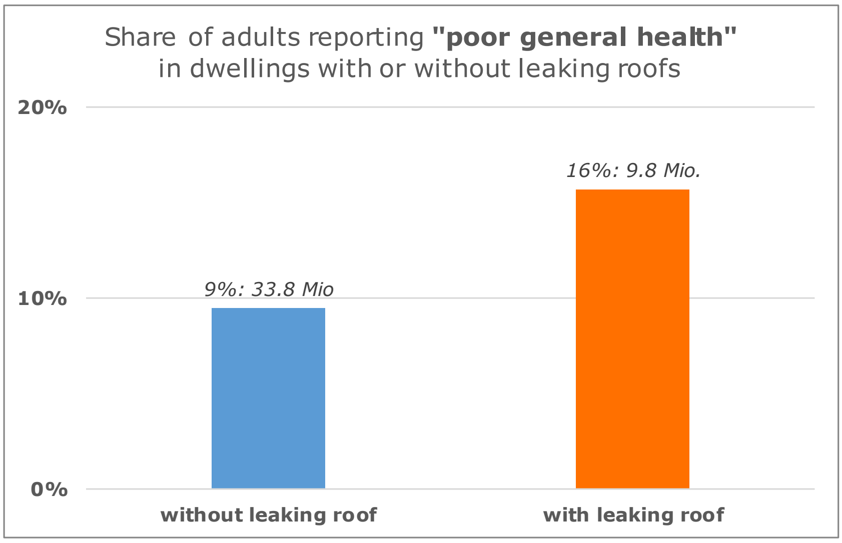


Figure 1: Health status in damp buildings for EU28 (share within subset and number of adults)

3.2. Health in dark buildings

Approx. 6% of all EU households (14 million; or approx. 30 Mio adults) report a lack of daylight

- When adults report no lack of daylight 10% report poor health
- When adults report lack of daylight 15% report poor health

The probability that adults report bad health is significantly higher when a lack of daylight is perceived; across the EU this probability is 1.5 times the one when no lack of daylight is perceived. Altogether approx. 10% of all adults reporting poor health live in buildings lacking daylight, where only 7% of all adults live.

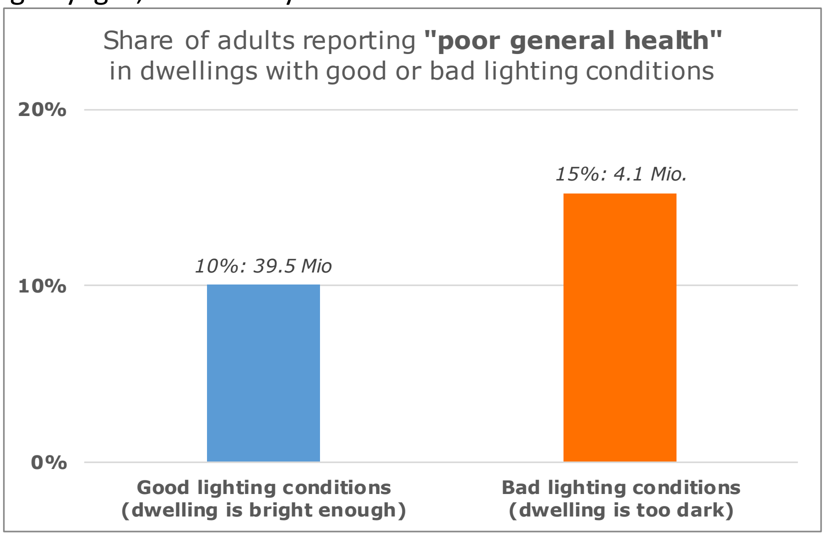


Figure 2: Health status in dark building for EU28 (share within subset and number of adults)

3.3. Health in overheated buildings

Approx. 20% of all EU households (40 million; or approx. 84 Mio adults) report bad thermal comfort in summer.

- When adults report good thermal comfort (cool dwelling) in summer 10% report poor health

- When adults report bad thermal comfort (too hot dwellings) in summer 13% report poor health

The probability that adults report bad health is significantly higher when bad thermal comfort is perceived; across the EU this probability is 1.3 times the one when good thermal comfort is perceived.

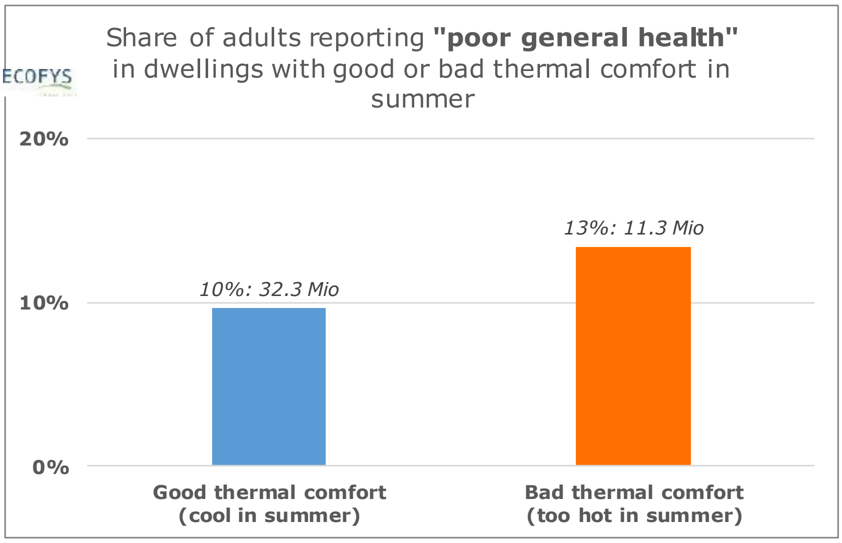


Figure 3: Health in overheated buildings for EU28 status (share within subset and number of adults)

3.4. Health in too cold buildings during winter

Approx. 15% of all EU households (more than 30 Mio; or more than 60 Mio adults) bad thermal comfort in winter

- When adults report good thermal comfort (warm dwellings) in winter 9% report poor health
- When adults report bad thermal comfort (too cold dwellings) in winter 16% report poor health

The probability that adults report bad health is significantly higher when bad thermal comfort is perceived; across the EU this probability is 1.7 times the one when good thermal comfort is perceived.

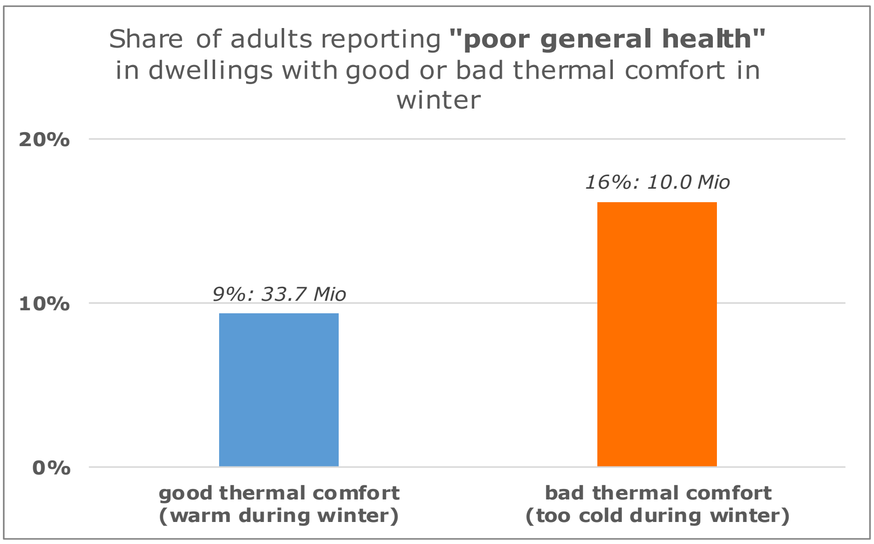


Figure 4: Health in too cold buildings for EU28 status (share within subset and number of adults)

4. Conclusion and discussion

The results described in this paper based on EU-SILC variables on quality of buildings and general health show statistically significant interdependencies. However, additional analysis are needed to understand for example the influence of economic issues of households and individuals, regional patterns or energy poverty on health. Based on the results shown here, we observed that structural problems of the building like leaking roofs, damp walls (etc.), buildings' ability to provide comfortable temperatures in winter, lack of daylight seem to act as similarly strong accelerators and/or indicators for health problems. On average the relative share of adults reporting poor health increases 30 to 70% when at least one of the above-mentioned deficiencies is reported compared to the group of people who do not perceive such deficiencies.

However, as indicated above this study so far focused on a small selected sample of relevant variables influencing health. On the other hand like in the analyses of Thomson and Snell (2012) who focused their EU SILC analyses on energy poverty, the strengths of the correlations are moderate. This is why on the one hand we found statistically highly significant correlations between the presented variables. This means, that there are many other variables apart from the ones analyzed in this study, also having a very significant impact on a person's perceived general health. Obviously personal and environmental variables determine health. Yet, we feel that buildings, which in this equation at least in Europe occupy 90% of the environmental variables' time are very much under-represented in today's overarching discussion about sustainability, which eventually is about shaping the world in a way that leads to sustained individual and societal health.

Above mentioned problems like dampness, darkness, too cold in winter or overheating in summer clearly hint at buildings in need of renovation. According to EUROSTAT (2012), ca. 58% of EU's population live in detached and semi-detached single family homes; our results also show that around 4 out of 5 of these dwelling types are owned by private owners. This means, that this group is crucial to successfully increase the renovation rate as implicated in the proposal for the amending directive on energy performance of buildings (European Commission, 2016) and needs to be addressed by incentives, renovation policies and awareness raising as well as information campaigns.

To reveal more insights, further research is ongoing to examine the linkage between health and building status, but also considering the economic status of building's occupants. This analysis considers additional variables such as health prevalence of building occupants for example due to age, occupancy status and, economic status, income level, existing chronical illnesses, medical care system of respective country, etc. In this sense, a prediction model and additional multiple correlations for health considering selected variables of building and economic status and previous mentioned variables could reveal insights on the impact on health, but also more general insights into causes and effects within the triangle of clusters of variables described above. Furthermore, analysis shall evaluate the development of the building and economic status as well as general health aspects over time to observe the impact of policy measures and to derive recommendations for priority areas for action. This can also reveal insights on causal chains between building status, economic situation and health aspects explaining energy poverty.

5. Acknowledgements

This research was supported by VELUX A/S. The research was conducted by experts from Ecofys Germany GmbH, with assistance of experts from VELUX A/S.

6. References

EUROSTAT (2012): DESCRIPTION OF TARGET VARIABLES: CROSS-SECTIONAL AND LONGITUDINAL. 2012 OPERATION (VERSION MAY 2013). ED. EUROPEAN COMMISSION. BRUSSELS.

EUROSTAT (2012). DISTRIBUTION OF POPULATION BY DWELLING TYPE. (ONLINE DATA CODE: ILC_LVHO01), ACCESSED 04.06.2017.

EUROPEAN COMMISSION (2016). PROPOSAL FOR A DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL AMENDING DIRECTIVE 2010/31/EU ON THE ENERGY PERFORMANCE OF BUILDINGS.

EUROSTAT (2015). POPULATION ON 1 JANUARY BY AGE AND SEX. (ONLINE DATA CODE: DEMO_PJAN). ACCESSED 04.06.2017.

EUROPEAN COMMISSION (2017): EU BUILDING STOCK OBSERVATORY. ONLINE: HTTPS://EC.EUROPA.EU/ENERGY/EN/EUBUILDINGS, ACCESSED 01.06.2017.

GRUEN, G. AND URLAUB, S. (2014): WHITE PAPER: TOWARDS AN IDENTIFICATION OF EUROPEAN INDOOR ENVIRONMENT' IMPACT ON HEALTH AND PERFORMANCE – HOMES AND SCHOOLS. FRAUNHOFER IBP. HOLZKIRCHEN. ONLINE: HTTPS://WWW.IBP.FRAUNHOFER.DE/CONTENT/DAM/IBP/DE/DOCUMENTS/PRESSEINFORMATIONEN/VELUX-PRESTUDY_WHITEPAPER_141205_AMENDED.PDF, ACCESSED 04.06.2017.

HERMELINK, A. AND JOHN, A. (2017). THE RELATION BETWEEN QUALITY OF DWELLING, SOCIO-ECONOMIC STATUS AND HEALTH IN EU28 AND ITS MEMBER STATES. SCIENTIFIC REPORT AS INPUT FOR HEALTHY HOME BAROMETER 2017. COLOGNE. ECOFYS BY ORDER OF VELUX A/S. ONLINE: HTTP://WWW.ECOFYS.COM/FILES/FILES/ECOFYS-2017-RELATION-BETWEEN-QUALITY-OF-DWELLING-AND-HEALTH-FINAL.PDF, ACCESSED 01.06.2017.

NEST (2004): NEST PROJECT, TECHNICAL UNIVERSITY OF BERLIN, EUROPEAN COMMISSION 2004. QUOTED FROM VELUX (2015). HEALTHY HOME BAROMETER 2015.

THOMSON, H. AND SNELL, C. (2012). QUANTIFYING THE PREVALENCE OF FUEL POVERTY ACROSS EUROPEAN UNION. ENERGY POLICY, 52 (2013), 563-572

VELUX (2015): HEALTHY HOMES BAROMETER 2015. ONLINE: HTTP://WWW.VELUX.DK/~/MEDIA/MARKETING/MASTER/DOCUMENTS/PDF/BROCHURES/VELUX_HHB_18032015.PDF, ACCESSED 01.06.2017.

VELUX (2016): HEALTHY HOMES BAROMETER 2016. ONLINE: HTTP://WWW.VELUX.COM/ARTICLE/2016/EUROPEANS-ON-HEALTHY-LIVING-THE-HEALTHY-HOMES-BAROMETER-2016, ACCESSED 01.06.2017.

VELUX (2017): HEALTHY HOMES BAROMETER 2017. ONLINE: HTTP://VELCDN.AZUREEDGE.NET/~/MEDIA/COM/HEALTH/HEALTHY-HOME-BAROMETER/507505-01%20BAROMETER_2017.PDF, ACCESSED 01.06.2017.

WHO (1946): CONSTITUTION OF THE WORLD HEALTH ORGANIZATION. ONLINE: HTTP://APPS.WHO.INT/GB/BD/PDF/BD47/EN/CONSTITUTION-EN.PDF?UA=1, ACCESSED 04.06.2017.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Impact of physical characteristics on comfort and well-being in selected neighborhoods of metropolitan Lagos, Nigeria

Mokolade B. Johnson[1], Anthony C.O. Iweka[1] and Michael Adebamowo[1]

[1] Department of Architecture. Faculty of Environmental Science,
University of Lagos, Akoka. Yaba. Lagos. Nigeria mokolade_johnson@yahoo.com. or mbjohnson@unilag.edu.ng. tel.+234-8056295050,+234-08082223779)

Abstract: People and their surroundings are principal factors that impact comfort and well-being in urban environments. Past research asserts that approximately half of the world's population presently reside in urban areas. However, due to rural-urban influx, pressure on existing basic infrastructure and amenities are on the rise, a situation which further compounds problems of residential inadequacy, urban heat island, crowding, environmental pollution, and other underlying societal challenges with direct effects on urbanite's well-being. Notwithstanding these glitches, there is paucity of information on how physical characteristics impinge on urban comfort which is critical for well-being. This paper explores the impact of 'physico-urban' characteristics on comfort and well-being and its implication on city planning. The study employed a multi-layered methodology through historical exploration and quantitative survey technique with questionnaire to residents of two (2) purposively selected municipals of Metropolitan Lagos. Findings show that in the Ikeja and Lagos Island localities, inadequate car parks constitute the main open spaces, there is a general lack of purpose built, people oriented, and accessible open neighborhood spaces designed for citizen's comfort and well-being benefits. A reformation of existing conditions can positively influence comfort, health and physical well-being of susceptible urban dwellers in a sustainable manner.

Keywords: comfort, physico-urban, physical well-being, sustainability, urbanization.

1. Introduction

Comfort is the state of awareness that expresses approval of the physical environment and is measurable by both objective and subjective estimation. (Johansson and Rohinton, 2006). According to versions of many dictionaries, comfort and well-being are synonyms. The discipline of well-being (or comfort), thermal comfort, and conception of a comfortable residential environment, was founded in the twentieth century, when it became practicable to regulate directly the -climate of environment like residences, workplaces, automobiles and other enclosures. Hitherto, indoor comfort settings were controlled by acclimatising procedures associated with behaviour, clothing, and the use of traditional devices to regulate temperature. Up till then, it was not beneficial to study the factors that could influence comfort. In order to study comfort, it was crucial to model the building as an uncluttered system and apply the principles of thermodynamics.

In similar studies, the European approach to the problem focused on the evaluation of the feel-good phenomenon. Pioneering research on confined spaces by Povl Ole Fanger (1934–2006), physiologist of the Technical University of Denmark, who focused on the relationship between the physical elements of an environment and the physiological parameters of people, and the perception of well-being as self-measured by the respondents. (Anger, 1967)

Comfort is the result of the relations of physical exchanges, physiological, psychological, societal and traditional rights, it depends on the architecture, the clothing, the eating lifestyles and the macroclimatic conditions. Similarly, research by others like Mendler later showed that the comfort of people in the work place is a very important criterion for their well-being. It was further established that human productivity increases/improves when they work in environments conducive to health. Amongst identified physical or objective measurable variables that can distress indoor work environment are poor natural or artificial lighting, poor ventilation, crowding, inadequate space, noise, lack of privacy and generally poor work environment. Sustainability as defined by The American Institute of Architects is the capacity of the people to continually function without decline through fatigue or overloading of vital resources on which survival system depends. (Mendler, 2000).

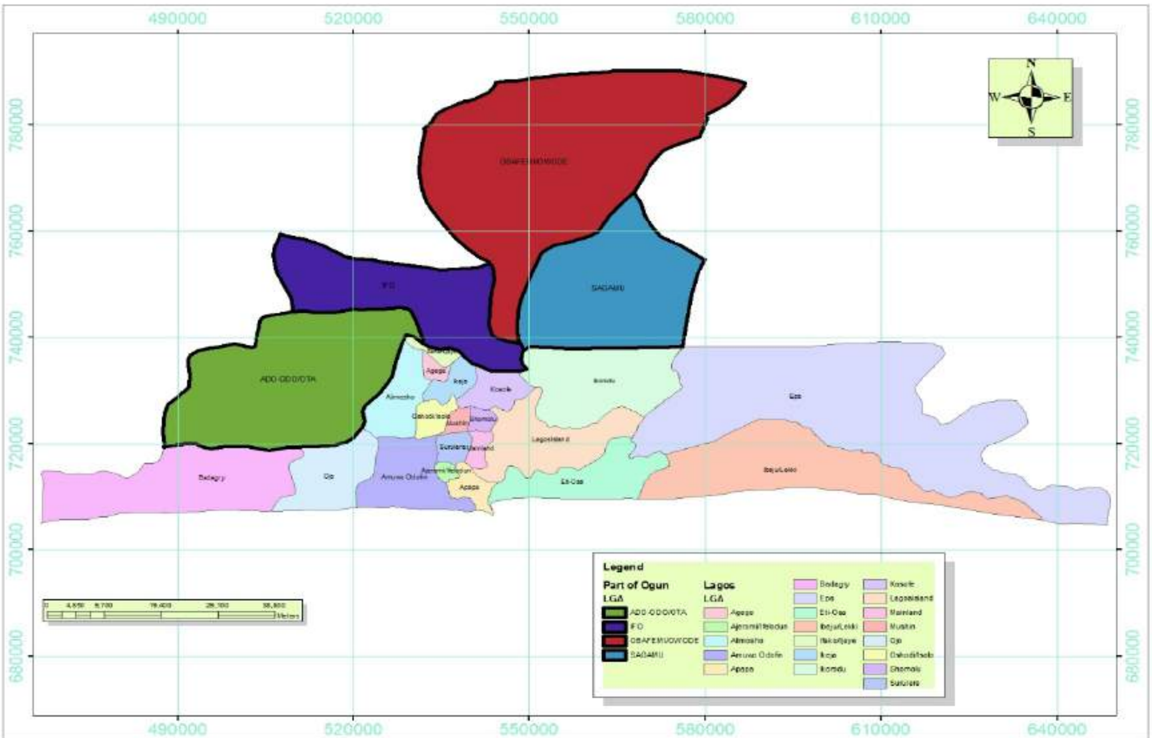
Thermal Comfort is also described as the study of the Adaptive Thermal Comfort (Olesen and Parsons 2002); Brager and de Dear 1998; Schweiker et al. 2012; Humphreys and Hancock 2007; Halawa and van Hoof 2012). In related studies, the comfort index introduced by Fanger is the Predicted Mean Vote (PMV) that permits respondents to express the score that a person gives to an environment, from the measurement of the physical parameters of the environment: air temperature, mean radiant temperature, air speed and humidity, and from the metabolic rate and clothing of the subject itself. (Olesen and Parsons 2002); (Brager & de Dear,1998); (Schweiker *et al*,2012); (Humphreys & Hancock,2007); (Halawa &van Hoof, 2012), (Mishra & Ramgopal,2013).

Another angle to the assessment of comfort and well-being is the establishment by research in several disciplines like Landscape Architecture, Urban Planning, Environmental Psychology and Human Ecology which posits that green infrastructure has significant contributions to urban milieu and its populations. Amongst the most pertinent foci is the connection that humans have links with the natural geographies, specifically with the green features which helps in conservation, creation of natural balance, enable urbanites to recreate, play, relief stress and socialize in order to achieve well-being. (Altman and Wohlwill, 1983); (Knopf, 1987). A extensive body of investigation in environmental psychology reveals that contact with nature, passive observation or participating in nature can engender progressive effects to resident's well-being with physical , psychological and social benefits .(Katcher and Beck, 1987); (Axelrod and Suedfeld, 1995). (Maller et al., 2005; Groenewegen et al., 2006). However, there is paucity of knowledge and information of these area of study in the Nigerian context and Metropolitan Lagos in particular.

2. Background to the study

2.1. The study area

Population distribution, industrialization, business, and lately computerization and other urban components are factors that shape the physical characteristics and determine the fundamental reorganization in operation concerning the growth of urban communities. Hawley (1969), Mabogunje (2002). Urban spaces are predominantly susceptible to the bearings of climate change, Lagos as the living environment of choice for a significant majority of Nigeria's populace is adversely affected by global warming's increasing stimulus on the urban climate, urban heat island (uhi) and the resultant effects on the comfort and well-being of a large percentage of the societies of the metropolis. In the local context, urbanization has been in continual crisis over a number of decades, and the problem is now operational Lagos. The Metropolis is a cross section –kaleidoscopic of the whole of Nigeria's urban life. Amos Hawley (1971). (Akinsemoyin et al 2009).The single most important view adopted from the social viewpoint by the study is based on the concept by archeologists which aptly treats the city as a physical phenomenon. The essential physical elements or characteristics includes; roads, residential walled enclosures, car parks, the streets, market place, the religious precincts with associated courts, administrative premises, the industries and workshops- a collection of these forms the physical characteristics of the study area. The urban geography of Lagos is constantly challenged by increasing demand for space, Mabogunje (2002), a crisis which continues to threaten the availability of open spaces which is beneficial to urban comfort. Other significant and major mark of urbanization apart from the physical structure is the magnitude of population concentration. However, this paper evaluated the availability or non-availability of open spaces in the Ikeja and as a proactive urban planning initiative in alleviating the urban heat island for comfort.



A map showing the boundary of Lagos.(Abiodun et al, 2017,Department of Survey & Geo-Informatics University of Lagos. Nigeria).

Rapid mass rural-urban migration is fast changing the standard of living in Lagos. Like most African cities, Lagos share these characteristics as both political and economic center confronted with varying challenges of a fast growing urban conundrum. With the backdrop of United Nation's (UN), (2009) forecast that approximately 75% of the world's population will live in urban centers by 2050. These trends of urbanization have some negative effects on urban climate such as urban heat island (uhi), bad air quality and lower air flow, which consequently affect the health and comfort of residents living in the cities. This indicates that better urban planning and design are of great significance to reduce the impact of built-up areas on the surrounding environments. (Ho et al 2015).There is a growing body of knowledge which insinuates that revealing the connection between the physico-urban attributes (quality &characteristics) of cities and the comfort or well-being of its residents will influence housing design perspectives with an inclusive understanding of comfort and well-being. Physico-urban attribute is described in the study as the physical quality and characteristics of elements that constitutes or form the composition of a particular urban built-environment which will have resultant effects on radiant and ambient temperatures of surroundings. (ASHRAE, 1999). (Lechner, 2008) Cities don't just grow, these phenomena are the bane of many modern urban societies. (Headey & Wearing, 1989); (Hendry & Kloep, 2002); (Cummins, 2010). Spatial expansion into informalities and influential externalities are significant factors shaping the attributes of urban sprawl that impact the comfort and well-being of urban dwellers in ways that suggests that the situation is getting beyond control (Mabogunje, 1968) ;(Warner & Kern (2013). Research by Mabogunje (2002), Moustafa, Y. M. (2009); UNHABITAT (2010) are replete with findings about the crisis of rapid urbanization. Historically, *Isale-Eko* as Lagos Island is otherwise known is the cradle-place of present day Lagos Island and by extension Lagos Metropolis, was chosen as part of the study area. Lagos is the place of origin of Nigerian politics and the socio-economic nerve-center of Nigeria. Godwin & Hopwood (2011). Lagos emerged as the economic capital West Africa immediately after the eradication of slavery in 1861. Akinsemoyin& Vaughan- Richards (2009). Lagos significantly transformed due to the evolutionary trend of urbanization and expansion in Sub-Saharan African cities because of unprecedented influx of people from other parts of Nigeria and the West African sub-region after colonial freedom. Adejumo (2010). Over the years, investigation also revealed the lack of proactive investment in efficient transport system, residential adequacy, pedestrian friendly foot-bridges, neighborhood parks, good roads, bike trails and healthy lifestyle enhancing facilities. All these were used as predictors for assessing the relationship between the city's physical environment and inhabitants' comfort and physical well-being. It is not expedient to imagine that these urban menace will be solved without holistic, people-responsive, design-led rethink and modelling the Afro-urban space. It was revealed that there are cumulative positive and negative effect of physico-urban amenities on in human thermal comfort and well-being. (Moustafa, (2009).). The way people live are traditionally predetermined by culture with a growing impact by advancements in technology. Babade(2008).

Within the last 50 years, economic indicators are the parameters which determines human comfort, but there is increase in the academic body of knowledge on this. (Layar, 2010), (Goodman, 2009). (Kuznets, 1933), (Perlman & Marietta (2005) argued that economic information about income, growth, productivity cannot be the only standard that influence the well-being and comfort. A large percentage of residential buildings in the study areas depend on mechanical cooling all year round at a huge financial energy cost and other associated expenses. Kusimo (2016). This has direct impact from the heat island effect because ambient temperatures in the hot-dry seasons ranges between 37^{0}C- 44^{0} in the face of worsening climate change. Also Wells and Evans found out that contact with nature can also relief stress and impact positively on well-being. These are drivers for reduction in expenses for health-care and comfort. (Wells *et al* 2010) and (Gilchrist 2012), the understanding of all these separately and collectively is central to knowing the effect of urban physical characteristics on comfort and well-being of urbanites. Current peri-urban studies also revealed the urban land development ratio as between 50%- 70% built-up to 20%- 30% open spaces around residential areas. .Altman (1993); (Fadera 2017). The World Health Organization's (WHO) classical definition states that health is not merely the freedom from sickness, disease or infirmity, but a favorable state of physical, mental and communal well-being. WHO (1948), Evans (2006). This assertion was corroborated by Altman and WHO's declaration which captures the essence of physical well-being as influenced by physical factors present in the physico-urban environment. This paper aligns with these assertions and posits that physical elements that constitutes the physico-urban environment like buildings, streets network, road network, sidewalks, pedestrian foot-bridges, bike trails, open spaces(parks), urban visual amenity, street furniture, general urban aesthetics, efficient drains, transportation, availability of natural environment(ecology) within urban precincts are indicators which are correlative to the interpretations and dimensions of measuring comfort and physical well-being. Wells, Evans, & Yang, (2010). The measurement of these physical attributes in scale, form, aesthetics, texture, size, color, condition, capacity amongst others are useful in determining both the objective and subjective aspects of urban comfort and well-being.

2.2. Urban spaces in relation to comfort and well-being

Open-air spaces are vital to sustainable and viable conurbations as they accommodate pedestrian traffic and outdoor activities, and add significantly to urban comfort and well-being. In the inclusive perspective of climate change, open spaces, walkways, parks and the integration of other physical amenities that provide a satisfying comfort experience for pedestrians efficiently enhance the worth of urban living and urbanite's well-being. The influence of urban open-air activities on comfort is a complex issue usually determined by planners, organization of the built environment, advancement in technology and the need for resident's comfort on the other hand. (Chen and Ng, 2011). The open-air atmosphere is worsening in many tropical metropolises due to uncontrolled urbanization resulting in a number of problems such as air pollution, poor air quality, congestion and crowding which are related to health and well-being. This seems to negatively affect physical outdoor activities that are beneficial to healthy lifestyles. The creation of thermally comfortable microclimates in urban environments is therefore very essential for healthy living. (Johansson and Rohinton, 2006), Gilchrist. (2012). It known from literature that urban comfort and well-being can be significantly affected by the availability or non-availability of natural features in the urban milleu. (Stokol, 1992), (Maller et al., 2005; Groenewegen et al., 2006).

Well-being is an inner state of good health comprising physical, mental and emotional state of harmony, which exists in a healthy environment (Burns, 1998) in which various involvement and experience with neighbourhood's green infrastructure and its attributes is contributory to residents' sense of well-being. Green infrastructure that is diverse is pleasurable and attractive and makes for lively neighbourhood settings by attracting different people at different times for comfort and heathy lifestyle activities. The more the diversity of the open spaces, the higher the level of engagement in trems of radiant and ambient temperature. The amount of greenery allows residents to view different landscape elements such as vegetation and water. The experience such as varying sunshade forms of trees ameliorates stress (Velarde et al., 2007), induce positive emotional responses and lower blood pressure (Lohr and Pearson-Mims, 2006), thus achieving perceptive comfort and well-being. Other research also pointed out that green spaces and nature have been found to enhance emotional well-being, reduce stress and, in certain situations, improve mental health (Ulrich et al., 1991; Ulrich and Parson, 1992).

3. Measuring Comfort and Well Being

Comfort is one of the criteria for well-being, which indicates that choice of material, spatial orientation and configuration, air movement, air quality, size, form and scale of physical amenities are important factors that satisfies comfort and urban well-being simultaneously. The study measured the ratio of built up area per building plot of average area 648m2 , to the 30% built-up and 70% open area according to government building codes . Since these dimensions are objectively measurable, the cumulative total can be taken as one parameter with values that can be used to determine the ambient comfort value for neighborhoods. This confirms that in the neighborhood with 271 households, the total area 17.5 ha, 30% translates to the open space planned for this area.

The rationale for developing a thermally desirable outdoor ambience in urban context has implications that go beyond the requisites of city design and well into the design of buildings. In order to re-establish and sustain life outdoors, it is important that urban spaces be made comfortable as far as the ambient climate allows. In order to ascertain conditions of comfort for outdoor spaces we need to define comfort for outdoors. Findings from a survey conducted on a large number of randomly selected people from Ikeja and Lagos Island are presented.

3.1. Proposed method of calculating physical well-being

Environmental footprint is operationalized as the average amount of land needed, per head of population, to sustain a typical neighborhood's need for physical amenities useful for resident's positive comfort and well-being value. It includes the land required to provide the renewable resources that humans use importantly for sustenance and shelter, the area occupied by infrastructure, and the area required to absorb generated heat. Significantly, it is a measure of need for physical attributes that can promote healthy lifestyles, not only production. Environmental footprint is expressed using a standardized unit: global hectares. A local hectare (ha) is a well-being productive area with average progress over a given period. (Veenhoven, 1996);(UNDP, 2015); (UN,2015)

4. Aim and Objectives

This paper explores the impact of 'physico-urban' characteristics of Ikeja and Lagos Island neighbourhoods of Lagos Metropolis on urban comfort and well-being of residents.

5. Methodology

The study employed a multi-layered approach through historical exploration and quantitative technique supported by structured questionnaire to randomly selected respondents in the Ikeja and Lagos Island neighbourhoods of Metropolitan Lagos. 271 household heads were randomly selected for self-assessment of available neighbourhood physical features like open spaces, accessible parks, quality of dwellings, pedestrian amenities like walkways, jogging, bicycle trails, drainage, water supply and car parking. The two localities were purposive selected because Lagos Island was the Nigerian seat of power till 1991, while Ikeja District is the capital of Lagos State till date. (Godwin & Hopwood, 2012).

The same instrument was applied to 35 residents of the Lagos Island neighbourhoods of Campos square, Ajele, Ita- Faaji, and Isale-Eko. This was augmented with historical information and observation of the areas for the impact of neighbourhood characteristics and the effect of the availability or non-availability of these on comfort and well-being of resident's.

6. Data presentation and Analysis

The physical elements in residential neighbourhoods are products of planning and design, it suggests that the evaluation of these features are central to understanding their performance in terms of resident's physical comfort and well-being as corroborated by Altman. The conceptual approaches commonly used in post occupancy evaluations, residential delivery and other residential research works advocates that urban residential buildings and their immediate environment should be able to satisfy the purpose for which they were designed. This suggests that physical comfort is influenced by the availability or non-availability of user-friendly and user -oriented amenities. (Parasuraman, Zeithanul & Berry 1985).This is crucial to the enhancement of resident's healthy lifestyle and well-being, as asserted, people do not just live within a physical environment - they interrelate with it and derive important meaning from it. (Altman 1993).

Table 1.Comfort and well-being indicators in Ikeja area:

Physical characteristics and services	N	Mean	MIS Rank
Sanitation –waste disposal	271	5.0738	1st
Parking facilities	270	5.0148	2nd
Plumbing	271	4.7196	3rd
Street furniture	271	4.5793	4th
Security	270	4.5630	5th
Roads	271	4.4244	6th
Drainage systems	270	4.4037	7th
Pedestrian amenities-walkway, jogging & bicycle trails	268	4.3619	8th
Electricity supply	264	4.1553	9th
Water supply	263	4.0989	10th
Open spaces	250	3.8000	11th

Table 2: Comfort and Well-being indicators

General comfort determinants	N	Mean	MIS Rank
Ventilation in your rooms at home	254	6.9094	1st
How peaceful is your neighborhood?	265	5.6075	2nd
How noisy is your neighborhood?	270	5.5259	3rd
How safe do you feel in your house any time of the day?	270	5.2407	4th
Can you let your children play around without getting worried?	270	4.8148	5th
No pollution in your neighborhood	264	4.7235	6th
Are houses fenced inside the neighborhood perimeter?	258	4.5736	7th
Do others use the spaces that belong to you?	267	4.4757	8th
How safe do you feel in the neighborhood any time of the day?	266	4.1353	9th

The questionnaire was subjected to Cronbach's reliability test before administration at the selected areas. The descriptive analysis method was used to rank the amenities.

The descriptive statistics shows the rating of the physical features and services present in the neighborhood on a scale of 1-7., with physical exercise amenities in the residential neighborhood rated 'very poor' with a mean score of 3.8000.

Table 3: Identified outdoor characteristics in study areas.

	Objective well-being	Subjective well-being	Well-being score average 1=low 7=highest
	Width of walkways/sidewalks	Comfort and privacy	1
	Physical conditions of neighborhood roads, drainage.	Neighborhood safety	1
	Adequacy of Parking spaces	Residential comfort satisfaction	1
	Open spaces—recreative activities, physical exercises, sports, bicycle and jogging trails	Privacy, recreation, interaction	1
	Separation of pedestrian and vehicular traffic.	Interactive inclusiveness	1
	Efficient drainage system	Sanitation and safety	1
	Availability of Schools-crèche, primary schools		2
	Children's playground	Relaxation and education	1
	Accessibility to other urban neighborhoods		3
	crowding	Lack of privacy	1
	Availability of healthcare facilities	Health	1
	Natural landscape feature	Ambiance and visual aesthetics or Amenity.	1
	Boundary fence	Residential security	1

6.1. Findings and Discussions

The physical quality and neighborhood characteristics of Ikeja and Lagos Island Municipals no longer reflect ethno-cultural values that can create a truly sustainable urban geography with the ambience of an accessible open or green spaces as an agent for regulating ambient and radiant temperatures for sustainable comfort and well-being. In the Ikeja municipal, it was found out that apart from open spaces in premises of private organizations and corporations, there is one open space of approximately 15000m^2 commissioned in 2017 by government for an estimated population of 4million urban dwellers. Lagos Island, is bordered by large car parks on the Marina. The new Oluwole Market car park, Onikan Stadium, Tafawa Balewa Square are major open areas, but are not freely accessible except to the paying public. Other open spaces like Ita-Faaji, Campos Square of approximately 5500m^2 are grossly inadequate for the comfort and well-being needs of a composite Central Business District. Lagos Island is the traditional seat of the ruler of Lagos, but the physical characteristics of the once quiet residential neighborhood of the 1800s no longer reflect the ethno-cultural values and identity of her cultural history. The only purpose-built public open space is the Tinubu Square commissioned in the early sixties. 80.7% of the respondents expressed the feelings of dissatisfaction in the neighborhoods in terms of comfort and well-being amenities. 87.9% of the neighborhood surveyed does not encourage physical activities that are beneficial to comfort and well-being living habits.

Ikeja and Lagos Island lack designated open space infrastructure network integrated into the planning of these municipalities for the urban populations. Ambient temperatures of surroundings can positively or negatively affect the thermal comfort of inhabitants with the integration of these physical features in the planning and design of cities.

Plate1.Lagos Island streets-1860-1954. Godwin& Hopwood (2012)

Plate 3.Aerial view of the Marina taken in 2008.

Plate 4. Onikan stadium in 2008.

7. Discussion and Conclusions

This paper posits that the concepts of design integrated accessible open space in urban milieus offer economic prospects in solving part of the major challenges of urban heat island, because open green spaces reduces neighborhood ambient temperatures significantly thereby positively impacting comfort and , and well-being of urbanites.(Wells et al ,2010). The use of open space in solving comfort challenges will reduce dependence on technology to solve comfort problems. Energy costs reduces while comfort level rises with a positive impact on climate change. It can safely be concluded that in rethinking thermal comfort, the level of comfort in of the individual is significantly dependent on natural physical feature of the particular area. The availability the physical elements will be useful for measuring and determining the comfort of inhabitants objectively.

7.1. Recommendations

The study proposes that design resourcefulness of urban municipalities should be sustainably redefined, planned, modified, maintained and managed through people oriented comfort and well-being enhancing development concepts. Though the Ikeja and Lagos Island were largely residential neighborhoods with pedestrian or resident friendly milieu until 1970s, urbanization pressures and challenges from 1960 to 2017 has converted and abused the functions of open spaces, street features that are good for citizen's comfort and well-being. Plates 1-4.

For a fast urbanizing Lagos to be a livable urban center by year 2050, this study recommends that a phase by phase urban restructuring and revitalization of neighborhoods should be priority for government, architects, urban planners and stakeholders to promote urban comfort and resident's well-being. Neighborhood physical features like green open spaces, pedestrianized walkways, footbridges, bicycle trails, that enhances comfort and well-being of residents should be integrated into existing and future urban neighborhoods to relief stress, build capacity, reduce energy consumption, economic costs and improve comfort level and well-being of urbanites sustainably.

8. References

Altman, I. (1993). Dialectics, physical environments, and personal relationships. Communication Monographs, 60, 26-34

Altman, I. (1975). The environment and social behaviour. Monterey, California: Brooks/Cole.

Abiodun O., Olaleye J., Olusina J. and Omogunloye O. (2017), Multi-criteria Regression Approach to Modelling Urban Expansion in Greater Lagos. Journal of Urban Planning and Development, Vol. 143, No 3.

Akinsemoyin,K and Vaughan-Richards, A.(2009).Building Lagos published by Prestige Books, Onikan, Lagos Island, Lagos

Axelrod, L. J., & Suedfeld, P. (1995). Technology, capitalism, and Christianity: Are they really the three horsemen of the eco- collapse? Journal of Environmental Psychology, 15, 183-195.

ASHRAE. (1999). 1999 ASHRAE HandbookH- VAC applications. Atlanta: American Society of Heating, Refrigerating and Air -Air condition- ing Engineers.

Chen L.and Ng E. 2011, Outdoor thermal comfort and outdoor activities: A review of research in the past decade https://doi.org/10.1016/j.cities.2011.08.006.

De Coulanges. F.(1956). The Ancient City:A Study of Religion,Laws and Institution of Ancient Greece and Rome.(Farden City, N.Y.:Doubledayn&Co.,1956),pp130-31

Gilchrist. K. 2012. Promoting wellbeing through environment: The role of urban forestry. School of the Built Environment, Heriot-Watt University, UK.

Godwin J. and Hopwood G., 2012, "Sandbank city- Lagos at 150". Published book. by Kachifo Ltd.Yaba. Lagos.

Groenewegen, P. P., van den Berg, A. de Vries, S., &Verheij, R. A. (2006) Vitamin G: Effects of green space on health, well-being, and social safety, BMC Public Health.

Jiboye, A. D., 2010.The correlates of public housing satisfaction in Lagos, Nigeria. Journal of Geography and Regional Planning, 3(2), 017-028.

Johansson E. and Rohinton E, 2006. The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka

Ho, J.CK, Ren C., Ng E. ,2015. A review of studies on the relationship between urban morphology and urban climate towards urban planning design in (sub)tropical regions. ICUC9-9TH Internationational Conference on Urban Climate with 12th Symposium on Urban Environment.

Katcher, A., & Beck, A. (1987). Health and caring for living things. Anthrozoos, 1, 175–183

Khandaker S. A., 2016. Comfort in urban spaces: defining the boundaries of outdoor thermal comfort for the tropical urban environments. https://doi.org/10.1016/S0378-7788(02)00085-3.

Lechner, Norbert. (2008) Heating Cooling and Lighting: Sustainable Design Methods for Architects. 3rd Ed. (New Jersey: John Wiley & Sons).

Mabogunje, A.L. (2002): Re-Constructing the Nigerian city: The new policy of urban development and housing.
Maller, C., Townsend, M., Pryor, A., Brown, P. and St Leger, L. (2005). Healthy nature healthy people: 'Contact with nature' as an upstream health promotion intervention for populations. Health Promotion International, 21,1, 45-54.
Ogunshakin, L. ,2005. Transforming Housing Environments through the Design. IAHS World congress on Housing, Pretoria South Africa. September 27-30 2005.
Parasuraman, A., Zeithaml, V. A., & Berry, L. L. (1985). A conceptual model of service and its implications for future research. Journal of Marketing, 49(fall), 41 – 50.
Rapoport , A. 1977. Human Aspects of Urban Form. Oxford: Pergamon.
UNDP, 2015. Human Development Report 2015. New York: United Nations. Retrieved from http://hdr.undp.org/sites/default/files/2015_human_development_report_1.pdf
United Nations (n.d.) World Population Prospects, the 2015 Revision: Population indicators. Retrieved from: http://esa.un.org/unpd/wpp/Download/Standard/Population
United Nations, 1968- 1969 ; Demographic Yearbook,pp.317-322 and 1969 pp.144-150.
Veenhoven, R. ,1996. Happy Life Expectancy: A comprehensive measure of quality-of-life in nations. Social Indicators Research 39:1-59.
Wells, N.M., Evans, G.W. and Yang, Y., 2010. Environments and Health: Planning Decisions as Public-Health Decisions, Journal of Architectural and Planning Research, 27(2), 124–143.
Wells, N.M., and Yang, Y., 2008. Neighborhood Design and Walking: A Quasi-Experimental Longitudinal Study, American Journal of Preventive Medicine, 34(4), 313–318.
WHO ,2010, International workshop on Housing, Health and Climate change- developing guidance for health in the built environment- mitigation and adaptation responses.

A study on seasonal indoor thermal environment in condominiums under the use of HEMS system

Rajan KC [1], H.B. Rijal [1], M. Shukuya [1], K. Yoshida [2]

[1] Tokyo City University, Graduate School of Environmental and Information studies.
[2] Tokyu Real Estate Co.Ltd, Next Generation Engineering Research Center

Abstract: Energy management in an effective way is important in building sectors including residential buildings. So, the uses of smart devices and energy management system have dragged the attention of developers and buyers in housing industries. The use of Home Energy Management System (HEMS) is increasing. The Japanese government also aims to set up HEMS to all of the new dwelling by 2030. Thermal comfort is associated with the trend of energy use in a building. In order to find out the thermal environment of the occupants living in smart houses, we conducted a measurement survey in a condominium equipped with HEMS. Indoor air temperature and relative humidity was measured for one year. The result showed a large variation in indoor air temperature and relative humidity during the study period. The occupants behaved differently according to flats, floor and seasons. The indoor air temperature in summer was observed higher as recommended in Japan. Due to high insulating materials used in the building, the indoor air temperature was not low even in winter. The result indicates that the occupants behaved differently to adjust the indoor thermal environment even during the use of HEMS.

Keywords: HEMS, Indoor environment, air temperature, relative humidity, occupants' behaviours

1. Introduction

Household energy use has been increasing due to increasing use of modern appliances like air condition, computer, electric toilet pans, DVDS etc. which are basically used to make the lifestyle easier and better. For sustainable energy use, it is important to manage energy use properly and effectively. Energy management in an effective way is more important in building sectors including residential buildings. The use of smart devices and the use of energy management system are the major concerns of developers and buyers in housing industries in most of the major economics including Japan (TMR, 2015). HEMS has become one of the popular energy management system. HEMS are linked from the visualization of electric power use to create smart home environment to power control of home appliances. The type and the number of home electric appliances determine the electricity use and also influence indoor thermal environment in domestic buildings (Firth, 2016).

Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ASHRAE 55, 2004). Indoor thermal environment and thermal comfort is associated with the trend of energy use in a building. Heating or cooling is the main reason for indoor energy use which may create suitable built environment during winter and summer. Comfort temperature and mean indoor temperature is highly correlated (Nicol, 2017). Those living in coldest region may enjoy sufficiently warm built environment, while on the other hand, those in temperate regions may not perceive warm enough due to a lack of proper heating systems (Cao, 2016). But the thermal environment in smart living has not been investigated yet. In order to know the indoor thermal environment equipped with HEMS, we need to conduct a measurement survey and analyse how the thermal environment varies in those houses. For this purpose, long-term measurement of indoor air temperature in smart living was made and its results were analysed.

The results will be useful to understand actual thermal environment in smart living. The temperature variation result will also be useful to understand the trend of energy use along with the use of HEMS. The result might be also fruitful for effective use of HEMS.

2. Field survey

A HEMS managed residential building in Shinagawa of Tokyo area has been selected for this study. The study site, Shinagawa is in south-west of Tokyo metropolitan area. The general climatic profile is warm and temperate. Annual precipitation is 1469 mm. The hottest month is August with average maximum temperature of 31.6°C and the coldest is January with average minimum temperature of 1.8°C. The monthly average relative humidity is highest in September and it is 86%. The lowest is in January and it is 54.7%. Annual relative humidity along with outdoor air temperature and indoor air temperature variations are given in section 3.1.

An eighteen storied condominium with 356 families shown in the Figure 1 (a) was selected for this study. Most of the studied flats in the condominium are 3 LDK (3 bed rooms, one living room including dining and one kitchen) and a few are 4 LDK (4 bed rooms, one living room including dining and one kitchen). The area of the flats varies from 71 to 90 m^2.

(a) Studied building (b) Device used for measurement

Figure 1 The studied buidling and the device used for measurement.

We kept measurement device as shown in Figure 1 (b) in 356 flats of the studied condominium. Measurement was carried out at an interval of 2-10 minutes to understand the indoor air temperature and relative humidity. The outdoor air temperature and relative humidity was taken from the Tokyo meteorological station, which is just 13 km far from the study area. The measured data has been averaged to a 10-minute interval so that they match the interval of outdoor air temperature.

3. Results

3.1. Monthly indoor and outdoor air temperature

The relationship between monthly mean indoor and outdoor air temperatures was investigated to understand how the indoor air temperature fluctuated corresponding to outdoor air temperature. As shown in Figure 2, the fluctuation of indoor air temperature is quite similar to that of outdoor air temperature but the amplitude is smaller. Realized indoor air temperature is different from one month to another. The difference between indoor and outdoor air temperature is large in January and small in August. The indoor air temperature is almost 20°C for the months with monthly outdoor air temperature below 10°C; that is, in January, February and March. The highly insulating materials used in the building is one of the causes of this temperature difference besides heating use, because similar trend is observed even with those flats of less heating use, which was estimated from the indoor air temperature variation trend. Similar result has been obtained from the study done in residential buildings in China (Luo, 2015).

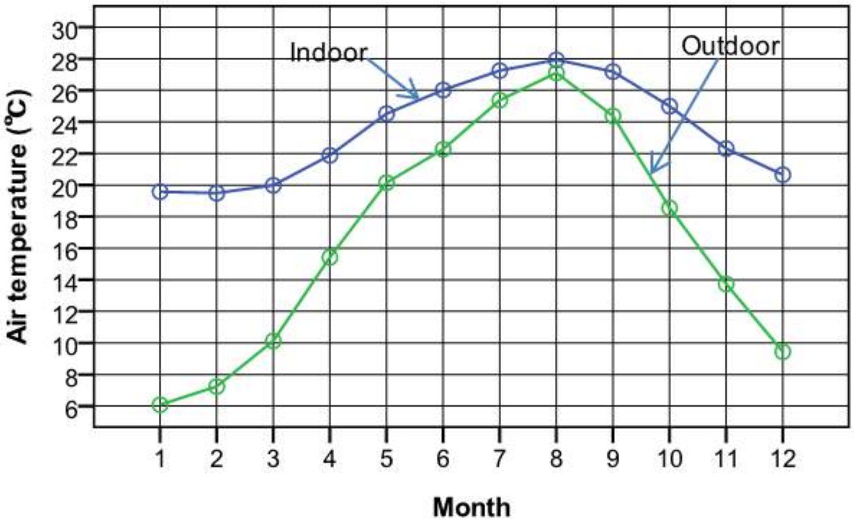


Figure 2 Monthly indoor and outdoor air temperatures.

3.2. The relation of indoor and outdoor air temperature of studied flats in different seasons

Figure 3 shows the relationship between indoor and outdoor air temperatures in respective four different seasons for the whole year. The indoor air temperature in spring and autumn seasons tend to be highly correlated to the outdoor air temperature. In winter season, the indoor and outdoor air temperature difference is quite large; the indoor air temperature is much higher than outdoor air temperature. It is due to the highly insulating materials used in the building along with the use of heating. In summer, the difference between indoor and outdoor air temperature is quite small. The linear regression equations for each of three modes are as follows:

Winter T_i=0.196T_o+20.21(n=78775, R^2=0.09, S.E.=0.002, p<0.001) (1)
Spring Ti=0.334T_o+19.02 (n=82112, R^2=0.48, S.E.=0.001, p<0.001) (2)
Summer T_i=0. 236T_o+23.61(n=804062, R^2=0.28, S.E.=0.001, p<0.001) (3)
Autumn T_i=0.391T_o+19.74(n=82951, R^2=0.66, S.E.=0.001, p<0.001) (4)

where, T_i is indoor air temperature (°C); T_o is outdoor air temperature (°C); n is number of votes; R^2 is the coefficient of determination; S.E. is standard error of the regression coefficient and p is the level of significance for the regression coefficient.

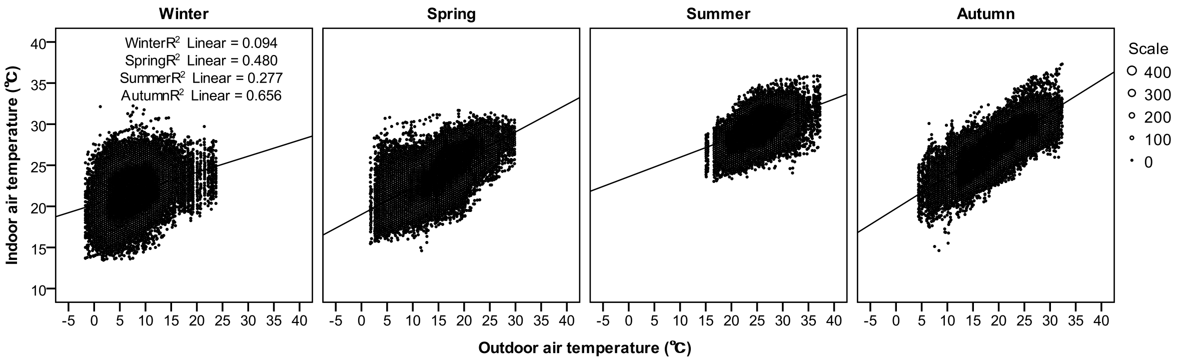


Figure 3 The relation of indoor and outdoor air temperature in different seasons

3.3. Indoor air temperature of different floors

The indoor air temperature of different flats according to floors was observed to know whether the indoor air temperature is different according to the levels of floor or not. The results showed that the temperature variation was different according to floors as shown in Figure 4. But, this difference was observed due to behaviors differences rather than floor level except the eighteenth floor. The eighteenth floor has the lowest indoor air temperature among all, because this is the topmost floor and the flats in this floor lost heat from the ceiling.

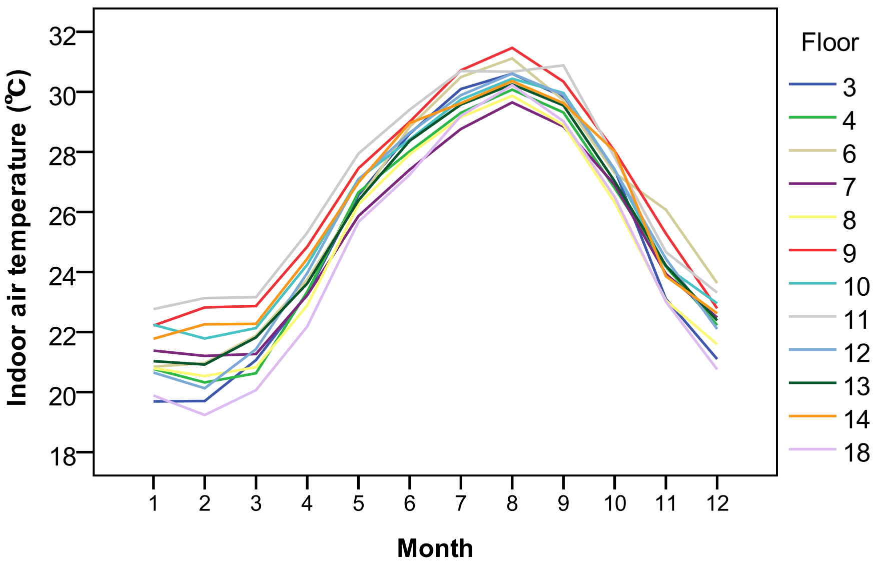


Figure 4 Indoor and outdoor air temperature according to floors.

3.4. Indoor air temperatures in different seasons

The seasonal variation of the indoor air temperature is calculated to understand the influence of seasonal change in indoor environment. We found the seasonal variation of indoor air temperature in the studied building (Figure 5). The mean air temperature is 27.1°C in summer and 20°C in winter. The autumn mean air temperature is 2.1°C lower than summer and 3°C higher than spring seasons.

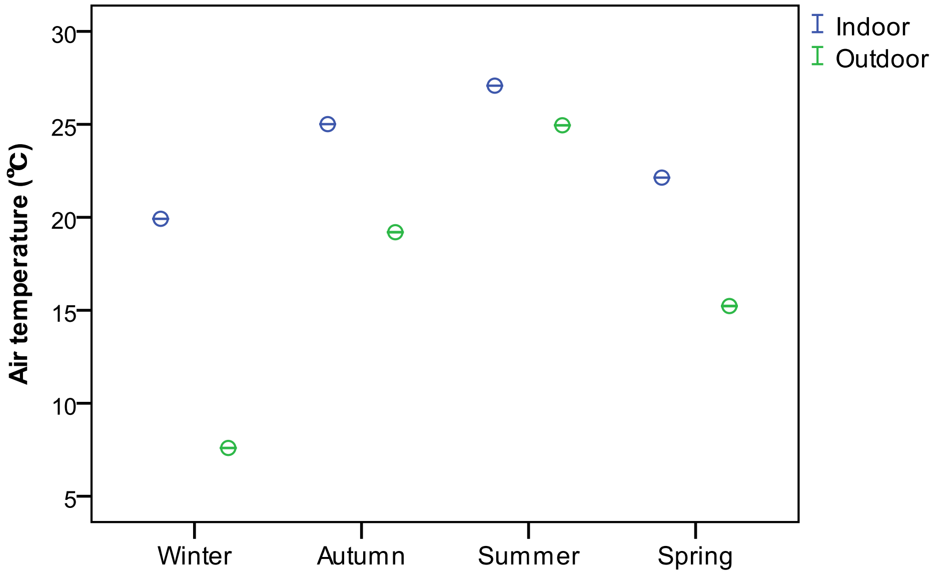


Figure 5 Seasonal differences in indoor air temperature

3.5. Seasonal differences by location

The mean indoor air temperatures with 95% confidence interval (Mean ±2 S.E.) in two different positions (center and corner) were analyzed from the measured data according to seasons. Figure 6 shows that the location of the flat in the building has influenced the indoor air temperature in different seasons. Flats at the center have slightly lower higher temperature than the flats at the corner. The studied building has the south main orientation so the flats in the center loose heat from north and south sides only, but the flats located at the corner loose heat from three sides including east side for east corner flats and west side for west corner flats.

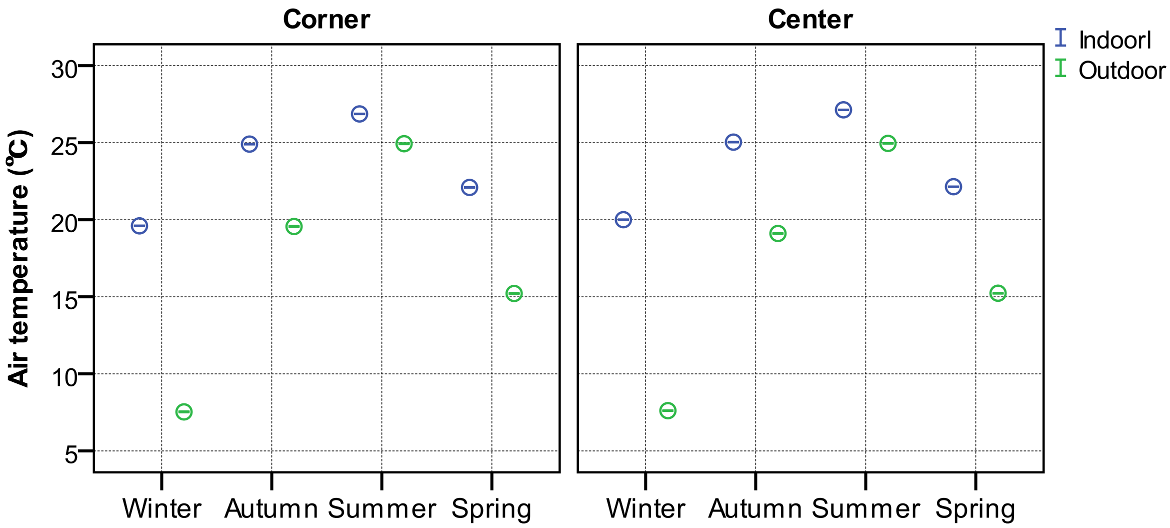


Figure 6 Indoor air temperature according to the location

3.6. Seasonal differences in indoor air temperature by months

We observed the mean indoor air temperature of four months representing to all seasons according to the floors. As shown in Figure 7, the result showed that the mean indoor air temperature ranged from 19 to 31.5°C in different seasons in different floors. The seasonal change of indoor air temperature doses not necessarily look consistence with each other. For example, the indoor air temperature of floor 15 has the highest temperature among all the floors in January, but floor 9 has the highest temperature among all the floors in August. The difference between indoor and outdoor air temperature is high in January and low in August. This suggests that the indoor environment has been influenced by the occupants' behaviors rather than floor level in the studied condominium.

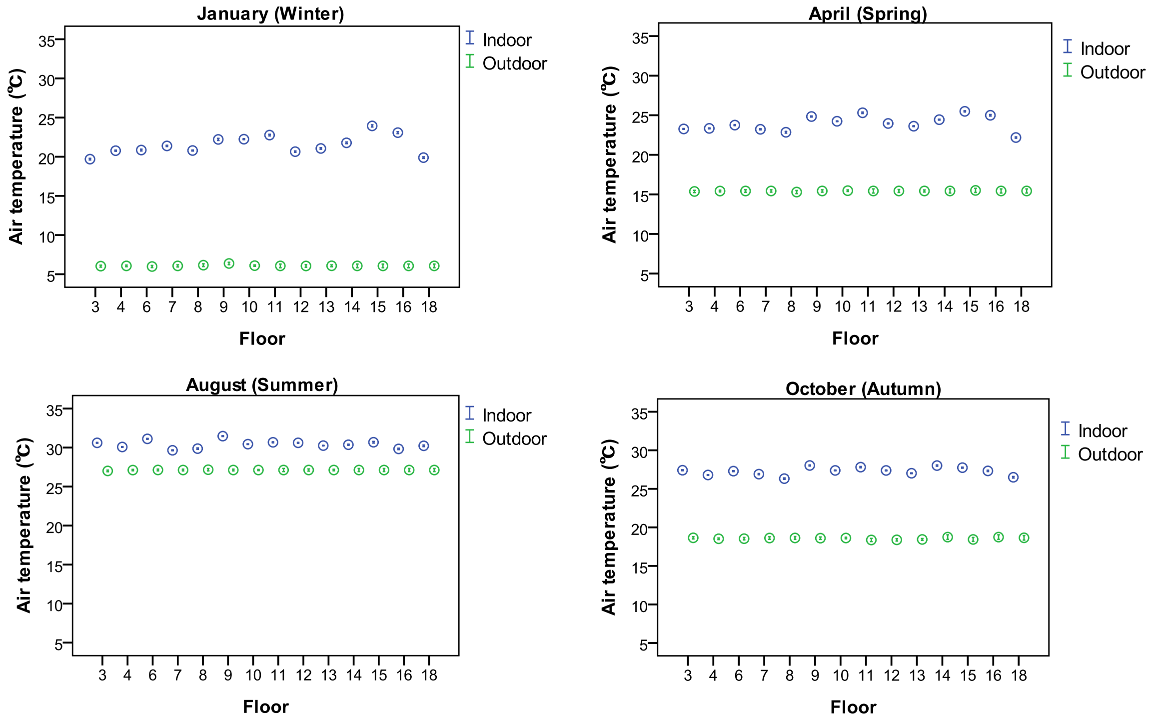
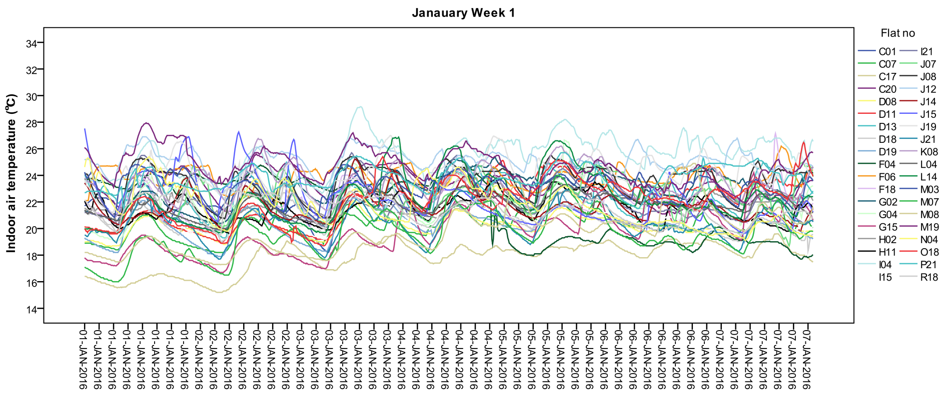


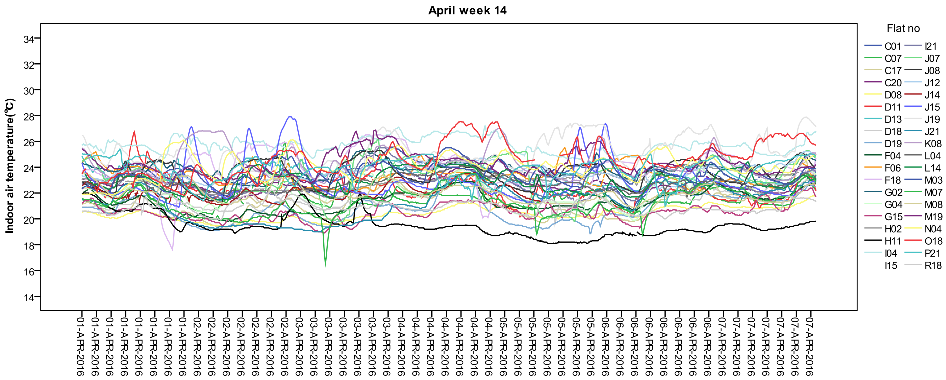
Figure 7 Indoor air temperature of representing months of all seasons

3.7. Weekly variation of indoor air temperature

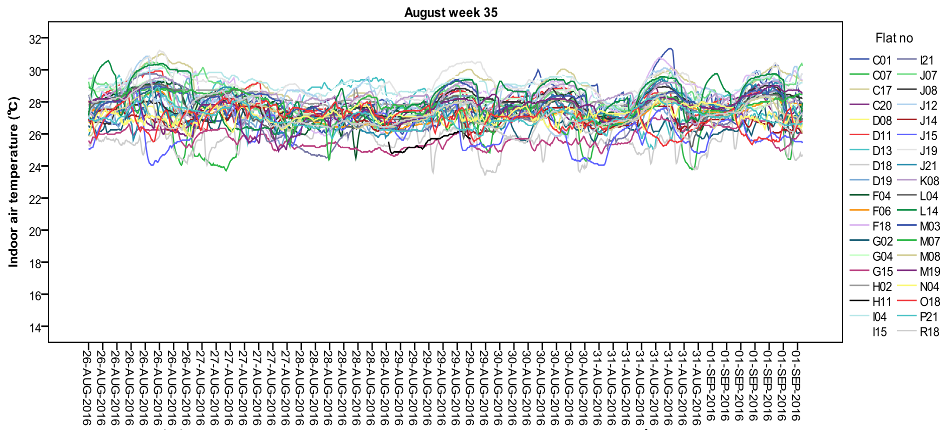
In order to understand the indoor air temperature variation associated with heating or cooling use or not, we observed one week indoor air temperature variation of different flats during different seasonal weeks. As shown in Figure 8 (a), in the first week of January, the fluctuation of indoor temperature is observed large due to the use of heating. The heating was mostly used in night time but the trend of heating use seems different according to the flats. The temperature fluctuation in April week is small as shown in Figure 8 (b). The occupants used very less energy for heating. In August, the fluctuation of indoor air temperature is very small in the studied week as shown in Figure 8 (c). Mostly, the temperature ranged between 28-32°C. This trend proves that the use of cooling is not so high. The trend showed that heating and cooling use vary according to the families. The result obtained is quite similar to the study done in individual *248 individual houses in UK (Heubner, 2013)*. The occupants might have adapted other behaviors like window opening, using less cloths or used fan. The indoor temperature variation trend in October week is quite similar to August week but the temperature is lower than August week (Figure 8(d)). Possibly, it is due to low outdoor air temperature.



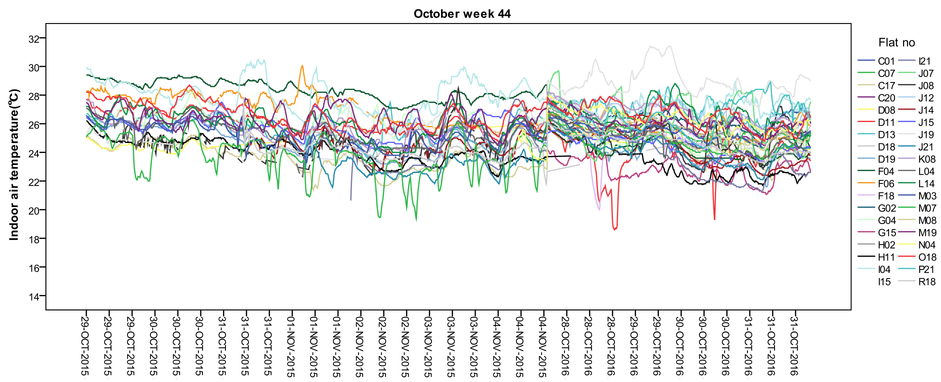
(a) Weekly indoor air temperature in January



(b) Weekly indoor air temperature in April



(c) Weekly indoor air temperature in August/September

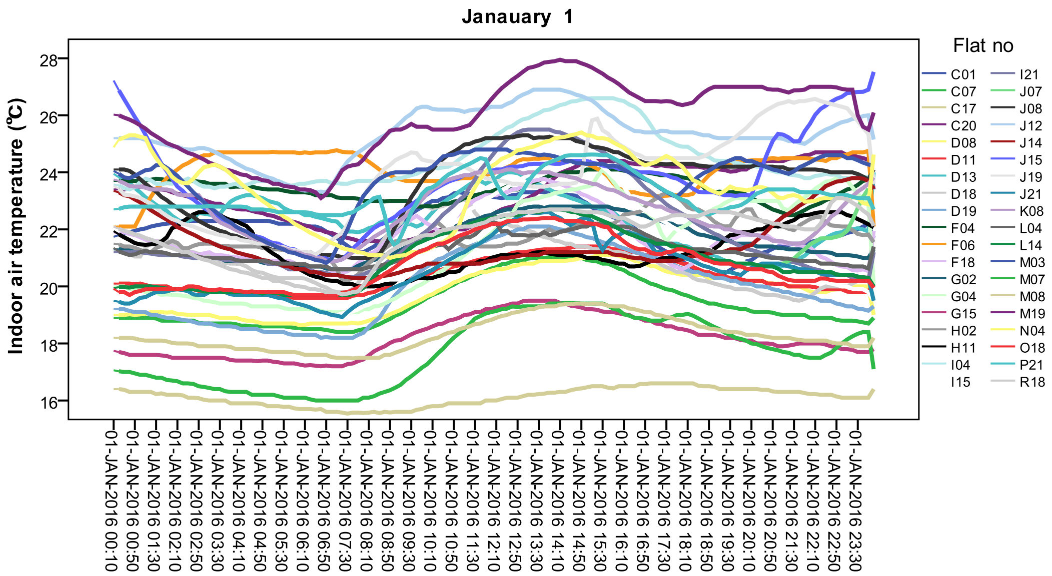


(d) Weekly indoor air temperature in October/November

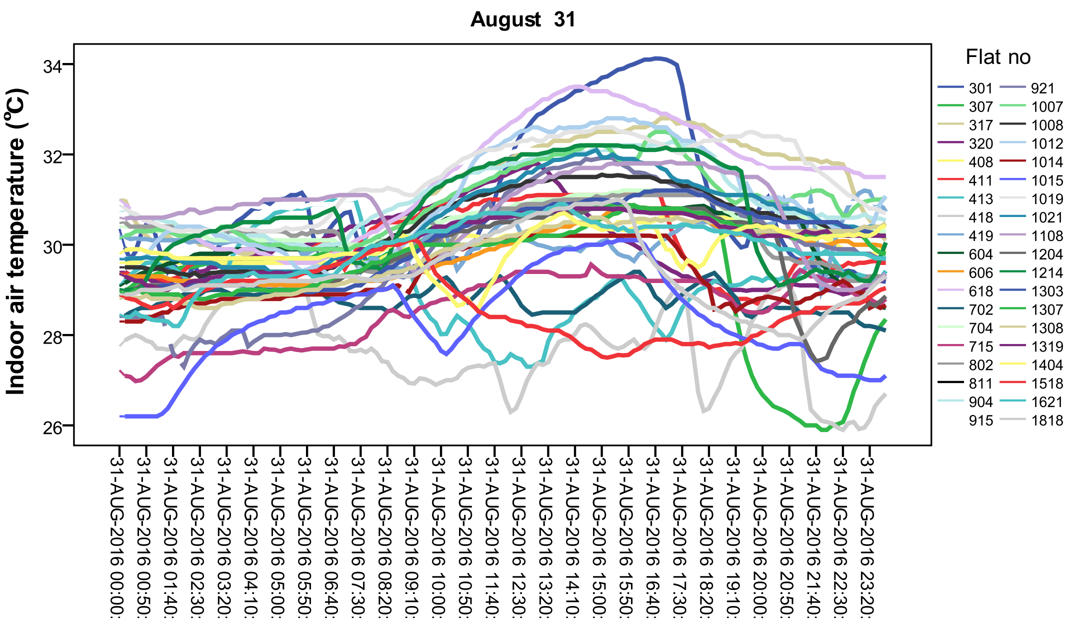
Figure 8 Weekly indoor air temperatures of different seasonal weeks

3.8. Daily variation of indoor air temperature in summer and winter

In order to understand the indoor air temperature variation we observed one day indoor air temperature variation of different flats of summer and winter seasons. As shown in Figure 9(a), the temperature decreased in the morning time. The temperature gradually increased in day time and again decreased in the evening time. At 20:00 pm onward, the indoor air temperature increased again due to heating use. The occupants were observed using heating in the evening time only. The heating use is done till 12 am. As discussed above, the cooling use is not strongly used because the band between indoor air temperature and outdoor air temperature is quite less. In the day time, the temperature is high due to solar radiation except some few flats.



(a) Daily indoor air temperature in January



(b) Daily indoor air temperature in August

Figure 9 Daily indoor air temperatures of winter and summer months.

3.9. Indoor and outdoor relative humidity

Relative humidity depends on temperature. It requires less water vapour for high relative humidity at low temperatures and more water vapour for high relative humidity in high temperature. Figure 10 shows that the indoor relative humidity is consistent with outdoor relative humidity in different seasons though the indoor relative humidity is lower than the outdoor. Figure 11 shows the relative humidity and water vapour concentration of different studied flats. The relative humidity of the studied flats is different but there is no big change in the amount of water vapour concentration. Possibly, the use of humidifier and dehumidifier is not so high.

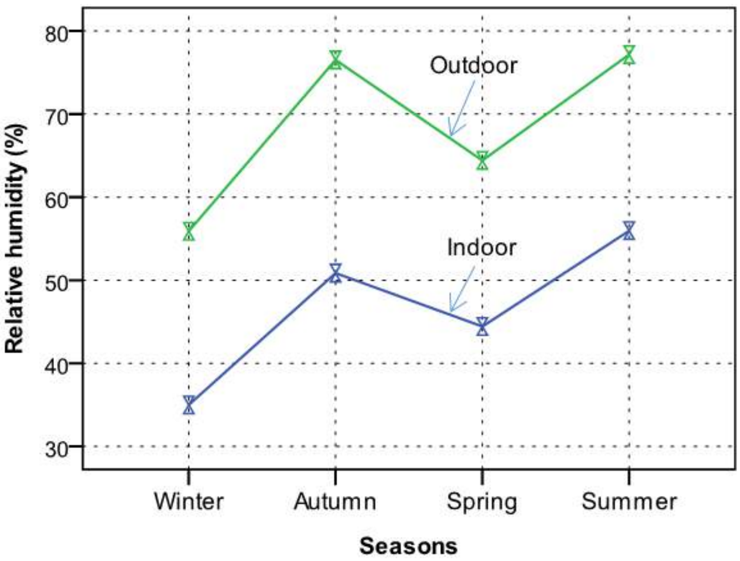


Figure 10 Seasonal relative humidity

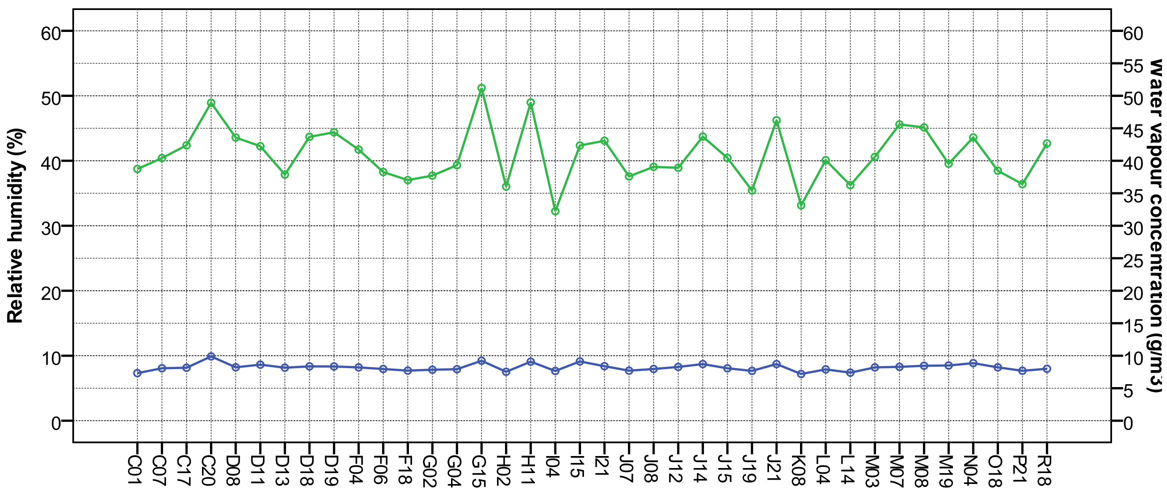


Figure 11 Relative humidity and water vapour concentration

Table 1 shows seasonal mean indoor and outdoor air temperature and relative humidity of all the selected flats. The result showed that the indoor mean indoor air temperature ranged between 16-24°C corresponding to 27-44% relative humidity in different flats in winter. But in summer, the indoor air temperature ranges between 27-29°C corresponding to 47-66% relative humidity in most of the studied flats. In spring and autumn, there is no large difference in indoor air temperature and relative humidity among the studied flats. The reason should be due to not using any heating and cooling devices.

Table 1 Seasonal indoor and outdoor air temperature and relative humidity of different flats

Flat No	Winter					Spring					Summer					Autumn				
	N	Ti	Rhi	To	Rho	N	Ti	Rhi	To	Rho	N	Ti	Rhi	To	Rho	N	Ti	Rhi	To	Rho
C01	9584	19.2	31.6	7.1	55.0	10810	22.6	42.3	15.0	65.2	4144	26.9	51.2	24.4	77.1	10131	25.7	51.2	20.8	78.7
C07	12959	19.4	30.0	7.6	55.9	13248	21.5	41.2	15.2	64.4	13248	26.9	54.4	25.0	77.2	12193	24.9	48.9	19.3	77.6
C17	12959	16.0	36.1	7.6	55.9	13247	21.0	42.0	15.2	64.4	13220	28.1	52.6	24.9	77.3	14114	24.3	48.9	18.9	75.6
C20	9495	20.1	43.5	7.9	56.2	13247	21.8	48.3	15.2	64.4	13248	27.2	54.2	25.0	77.2	12120	25.1	50.7	19.5	77.9
D08	12949	17.6	33.8	7.6	55.8	13237	20.4	44.6	15.2	64.4	13248	26.8	55.7	25.0	77.2	14374	24.2	50.2	19.1	75.5
D11	12959	20.9	32.2	7.6	55.9	13247	22.0	42.6	15.2	64.4	13248	27.2	53.9	25.0	77.2	13834	24.9	48.3	18.9	76.4
D13	12959	21.2	27.5	7.6	55.9	13248	23.3	38.8	15.2	64.4	13248	27.6	49.0	25.0	77.2	16334	25.4	44.1	18.8	75.1
D18	12959	19.3	32.6	7.6	55.9	13247	21.4	43.9	15.2	64.4	13248	25.4	56.8	25.0	77.2	12408	24.2	48.9	19.0	76.7
D19	12958	17.9	36.0	7.6	55.9	13200	21.0	44.2	15.2	64.4	12524	26.7	55.6	24.8	77.8	14963	24.2	49.5	18.9	75.7
F04	11763	18.9	30.7	7.8	56.3	13248	21.2	41.8	15.2	64.4	13248	27.6	52.2	25.0	77.2	13995	25.8	45.3	18.9	76.0
F06	12767	21.5	27.3	7.6	55.5	13248	22.4	38.1	15.2	64.4	13247	26.8	53.3	25.0	77.2	13883	25.1	45.2	18.9	75.8
F18	12086	19.6	29.9	7.4	55.6	8876	22.5	38.5	14.5	64.0	11256	28.8	49.8	25.0	76.6	11180	25.6	49.2	19.7	77.7
G02	12958	21.2	28.3	7.6	55.9	13248	22.8	39.4	15.2	64.4	13248	26.6	47.8	25.0	77.2	12025	25.0	46.5	19.4	77.6
G04	12622	19.9	29.1	7.6	56.2	13248	21.7	40.3	15.2	64.4	13248	27.3	51.1	25.0	77.2	14145	25.2	45.3	18.9	75.6
G15	12959	18.7	40.6	7.6	55.9	13211	20.1	52.1	15.2	64.4	13248	24.9	65.7	25.0	77.2	9658	23.6	60.4	20.4	77.4
H02	12959	19.8	25.6	7.6	55.9	13248	22.4	36.4	15.2	64.4	13248	27.6	51.1	25.0	77.2	10709	25.8	45.7	19.9	77.4
H11	12296	18.7	38.1	7.7	56.8	11976	20.4	49.7	15.2	64.9	9915	25.2	64.5	24.7	77.1	13673	22.9	57.3	18.5	75.3
I04	12959	23.5	21.4	7.6	55.9	13248	24.9	32.2	15.2	64.4	13249	28.7	48.5	25.0	77.2	15124	26.5	42.0	18.8	75.5
I15	6228	19.1	33.0	9.0	56.7	13248	22.1	40.0	15.2	64.4	13248	28.3	50.3	25.0	77.2	8929	27.1	47.1	21.3	78.3
I21	12901	18.8	33.2	7.6	55.8	13216	22.0	44.6	15.2	64.4	13246	26.8	56.7	25.0	77.2	12751	24.3	51.2	19.0	77.2
J07	12557	20.3	27.4	7.7	55.4	13096	22.5	37.7	15.3	64.4	13010	27.1	53.7	24.9	77.3	11548	25.4	46.2	19.5	77.3
J08	12844	21.4	28.2	7.6	56.0	13247	22.1	40.7	15.2	64.4	13248	26.9	52.6	25.0	77.2	10474	25.5	48.7	20.5	77.2
J12	12959	22.0	31.3	7.6	55.9	13248	22.9	40.2	15.2	64.4	13248	27.8	50.4	25.0	77.2	10192	26.5	45.2	20.1	77.1
J14	10974	19.4	35.3	7.5	55.9	10110	22.1	44.0	15.5	64.7	12495	26.8	55.0	25.0	77.1	12144	24.6	49.2	19.1	77.1
J15	12917	20.0	31.8	7.6	55.9	13248	22.2	41.6	15.2	64.4	13248	26.4	52.8	25.0	77.2	14781	24.4	47.9	18.8	75.5
J19	12937	22.2	27.0	7.6	55.9	13214	24.0	38.2	15.2	64.4	10681	28.4	51.5	25.2	77.2	14050	26.5	44.0	19.0	76.0
J21	12959	18.0	42.4	7.6	55.9	13247	21.5	45.9	15.2	64.4	13219	26.8	55.0	25.0	77.2	13049	24.0	51.4	19.0	77.1
K08	12959	21.2	23.8	7.6	55.9	13248	23.4	34.4	15.2	64.4	13248	27.8	46.9	25.0	77.2	16113	25.5	42.4	18.8	75.3
L04	12495	19.4	30.8	7.5	56.0	13189	21.8	40.9	15.3	64.5	13167	26.9	52.6	25.0	77.2	14565	24.7	46.7	18.8	75.5
L14	12959	19.1	28.5	7.6	55.9	13248	22.6	37.4	15.2	64.4	13248	27.6	46.9	25.0	77.2	15881	25.4	42.4	18.8	75.3
M03	12959	20.3	34.5	7.6	55.9	13248	22.3	41.1	15.2	64.4	13248	27.2	51.3	25.0	77.2	15714	24.6	46.6	18.8	75.4
M07	12959	17.7	39.0	7.6	55.9	13242	20.9	47.5	15.2	64.4	10508	27.1	56.7	25.0	76.0	14485	24.0	51.2	18.8	75.4
M08	12959	18.5	38.8	7.6	55.9	13247	21.1	45.8	15.2	64.4	13248	26.7	52.6	25.0	77.2	12425	24.9	47.3	19.3	77.3
M19	11603	22.5	31.0	7.7	56.3	13247	23.6	38.5	15.2	64.4	13244	27.0	55.4	25.0	77.2	14822	25.5	46.7	18.8	75.5
N04	12959	20.4	37.9	7.6	55.9	13248	22.6	43.9	15.2	64.4	13248	27.2	53.2	25.0	77.2	12586	25.1	48.9	19.2	77.4
O18	12959	22.4	30.0	7.6	55.9	13109	23.5	39.9	15.3	64.4	13248	27.0	49.7	25.0	77.2	14232	25.5	44.4	18.9	75.6
P21	12959	22.0	27.2	7.6	55.9	13248	23.6	36.2	15.2	64.4	13248	26.3	49.5	25.0	77.2	9122	25.6	47.7	21.1	77.9
R18	12956	18.3	34.0	7.6	55.9	12819	20.9	43.6	15.4	63.8	13248	26.5	55.9	25.0	77.2	13188	24.0	50.1	19.0	76.9

4. Discussion

Generally, it may be considered that the occupants become fully dependent on the use of mechanical system for thermal environment if they live in smart houses because the energy use can be self-controlled or by automatic systems. The studied condominium is equipped with HEMS, which provides the occupants with the information about indoor and outdoor temperature condition, weather information or the amount of energy used for a particular device used indoors. So, the occupants living with such system can adjust the indoor thermal environment favourable to them with the use of mechanical heating and cooling. But, the results obtained here in this study showed that the occupants were not fully dependent on mechanical system only because the temperature variation in not uniform. The occupants living in this condominium are adapting various other activities besides the use of mechanical system. During summer, the indoor air temperature of some of the flats was higher than the recommended temperature for cooling that is 28^{o}C in Japan. The analysis so far proves that the adaptive behaviours have influenced the indoor thermal environment rather than the fully use of mechanical energy management system. If this knowledge is considered during the development and installation of any smart energy management system, it may be more applicable and long lasting.

5. Conclusions

From a series of analyses on the data collected by thermal measurement survey conducted in a HEMS condominium in Shinagawa, Tokyo metropolitan area in Japan, we have found the following results.

1. The indoor air temperature in the studied condominium was not similar according to flats or floors.
2. The location of the flats at the centre or corner has influenced the indoor thermal environment.
3. Daily, monthly and seasonal differences were observed in indoor air temperatures and relative humidity.

Acknowledgements

We would like to thank to all the occupants residing in Katsushima (studied building) for being cooperative during the survey.

References

ASHRAE Standard 55. Thermal environment conditions for human occupancy, Atlanta, GA 2004.

Cao, B., Luo, M., Li, M. and Zhu, Y., 2016. Too cold or too warm? A winter thermal comfort study in different climate zones in China. Energy and Buildings, 133, 469-477.

Firth, C. S., Lomas, K., Wright, A., Wall, R., 2016. Identifying trends in the use of domestic appliances from household electricity consumption measurements. Energy and Buildings, 40, 926-936

Huebner, G.M., McMichael, M., Shipworth, D., Shipworth, M., Durand-Daubin, M., Summerfield, A., 2013. The reality of English living rooms – A comparison of internal temperatures against common model assumptions, Energy and Building, 66, 688-696

Jo Luo, Q., Yang, L., Liu, N. X., and Xia, J., 2015. Comparative study on thermal environment and energy consumption of urban residential houses in Beijing, Procedia Engineering, 121, 2141-2148.

Nicol, F., 2017. Temperature and adaptive comfort in heated, cooled and free-running dwellings, Building Research & Information, 45:7, 730-744, DOI: 10.1080/09613218.2017.1283922.

Transparency Market Research's new market research report 2015. Home energy management systems market - global industry analysis, size, share, growth, trends and forecast 2013 – 2019.

WINDSOR CONFERENCE
Rethinking comfort
12th - 15th April 2018

Evaluation of subjective occupant thermal comfort in the selected buildings in upper east region of Ghana

Frederick W. Manu[1], Christian Koranteng[1] and Leonard K. Amekudzi[1]

[1] Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

Abstract: International thermal comfort standards such as the American National Standards Institute/ American Society of Heating Refrigeration and Air-conditioning Engineers (ANSI/ASHRAE) standard 55-2013, European Norn (EN) standard 15251-2007 and International Standards Organization (ISO) standard 7730-2005 have not been found to be true reflection of the response to thermal environments of people in the tropics. This has been reported by researchers such as Bouden and Ghrab (2005), and Dhaka et al. (2015). This has left a gap in understanding of thermal comfort in tropical regions such as Ghana in a real life situation. The goal of this study is to assess the subjective occupant thermal comfort in 12 selected buildings in urban and peri-urban areas of Bolgatanga, Upper East Region of Ghana. Furthermore, the specific objectives of the study are to assess prevailing environmental parameters, thermal comfort voting and distribution, and deduce a comfort temperature. The study area was carried out in the Savannah climatic zone of Ghana in the 6 warmest months of 2015. A longitudinal thermal sensation survey method was adapted with the intention of deriving long term data from relatively small number of respondents. The sample size of the survey was 144 occupants with 2 respondents for a month from each household**.** A thermal sensation questionnaire formulated comprised biodata, ASHRAE seven-point thermal sensation scale with a pictograph, and the McIntyre thermal preference scale. From the analysis, it was found out that 88% of the respondents found their thermal indoor conditions acceptable with a neutral temperature of 30.3°C derived through linear regression.

Keywords:, Thermal, sensation, comfort, subjective

1. Introduction

Assessing the subjective thermal comfort of occupants of a building leads to a complete understanding of how thermal comfort interacts with other elements of indoor environmental quality to influence overall occupant satisfaction. De Dear et al. (2013) acknowledged that the reinstatement of building occupants and experimental subjects as the final arbiters of thermal comfort over instrument observations, leads to a clearer understanding of thermal interactions between the occupants and buildings. The added benefits are achieving a better design and operation of buildings and building services. As a warming climate is widely accepted as the most likely outcome of climate change according to Nicol et al. (2016), maintaining an acceptable indoor climate depends on the specific climatic conditions of each region. There is therefore the need to determine acceptable indoor temperature for each climatic region. The option of using existing standards such as ANSI/ASHRAE 55-2013, EN 15251-2007 and ISO 7730-2005 have been found not to be a true reflection of thermal sensation in the tropics. This is because global and regional projects which were conducted to develop database for the standards such as Humphreys in 1978, ASHRAE Research Project 884 in 1998 and Smart Controls and Thermal Comfort (SCAT) in 1996-1998 were mostly in Europe and North America. In Ghana, there have also been a number of thermal comfort studies beginning with Small and Chandler (1967). The authors studied thermal comfort in an office buildings in Accra in 1958 with the results that comfort temperature was 26.8°C (Small and Chandler, 1967). Later there were studies conducted on offices in Kumasi by Koranteng (2011). Appah-Dankyi and Koranteng (2012) conducted a study in a school in Accra and found that respondents in tropical countries may have a higher heat tolerance. This is because the respondents accepted thermal conditions which exceeded the standard of between 26°C and 28°C (summer comfort range) by 1°C to 5°C . These standards have been carried out in the Dry Equatorial and Wet Semi-Equatorial leaving out the South-West Equatorial and Tropical Continental climatic regions. The Tropical Continental climatic region is the largest, warmest and driest. To begin a database of thermal comfort studies tht could lead to a future national and sub-regional standard the perception of residents from this climatic region would have to be represented.

The goal of this study is to assess the subjective occupant thermal comfort in the selected buildings in urban and peri-urban areas of Bolgatanga, Upper East Region of Ghana. The objectives of the study are to assess the prevailing environmental parameters, thermal comfort voting and distribution, and deduce a comfort temperature.The study area is located in the Tropical Continental climatic region of Ghana and was carried out in the 6 warmest months in the year which coincides with the dry season.

2. Methodology

2.1. Description of study areas

The study areas are located in the Bolgatanga Municipality and Bongo District of the Upper East Region of Ghana. The Central Business District (CBD) of Bolgatanga Municipality and Gowri, Kunkua and Sabodaa (Gowri-Kunkua-Sabodaa) communities in the Bongo District were selected for the study.

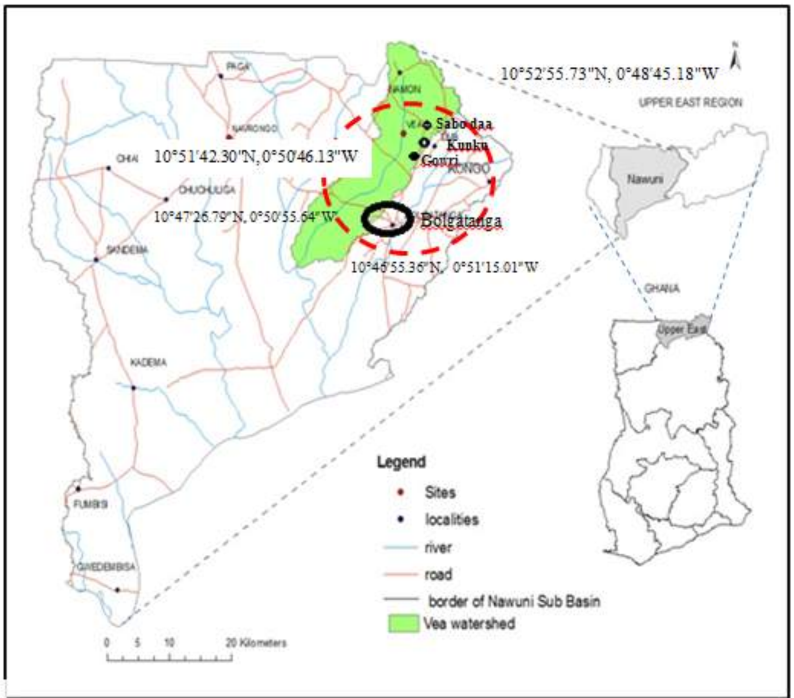


Figure 2.1: Map of the Upper East Region of Ghana
(Source: Centre for Remote Sensing and Geographic Information Services, University of Ghana)

Bolgatanga Municipality lies within latitude 10°47'17.22"N and longitude 0°51'5.66"W, and latitude 10°46'55.36"N and longitude 0°51'15.01"W. The three adjacent sprawling communities of Gowri, Kunkua and Sabodaa also lies within Latitude 10°52'29.55"N and Longitude 0°49'30.58"W, and Latitude 10°51'42.30"N and longitude 0°50'46.13"W as shown in Figure 3.1.

The communities were selected after a reconnaissance survey to select settlement potraying urban and peri-urban areas with typical residential buildings. The Central Business District of Bolgatanga Municipality was selected for its urbanised environment and the presence of typical earth and sandcrete buildings. The three communities of Gowri-Kunkua-Sabodaa were selected as peri-urban communities with buildings portraying typical characteristics of rural buildings. Gowri-Kunkua-Sabodaa lie between 10 and13km away from Bolgatanga. This region falls under the tropical continental climatic zone classified by Dickson and Benneh (1990).

There exist the WASCAL Eddy Covariance (EC) Station on Latitude 10° 50' 49" N and Longitude 0° 55' 1"W about 9 km and 13km (averagely) from station respectively from Bolgatanga and Sabodaa. The station delivers hourly climatic parameter data. The station has hourly climatic data from 2013 to date with some missing data though. This is necessary for thermal comfort studies.

2.1.1. Point-in-time assessment

Sampling for the study was divided into subject and survey sampling. In subject sampling, the selected respondents had experience with indoor and outdoor weather for at least two seasons. They fell within the age group of 15 to 60 years. During the thermal sensation survey, the respondent went about their daily routine unhindered in any clothing of their choice.

With the thermal sensation survey sampling, the longitudinal method was used. In this, a small number of subjects are selected to give a large data of comfort assessments over an extended period of time (Fergus et al. 2012). This method has the advantage of getting considerable information about a person or group as against the transverse survey method in which large number of respondents are chosen over a short time. In addition the longitudinal method made it possible to follow the respondents' responses over an extended time. This sampling method had been used in various field thermal comfort studies by Sharma and Ali (1986), Humphreys and Nicol (1970), Nicol (1974) and Webb (1964). There was the danger of sample bias as the sample size is small and not be representative of the whole population. To reduce this effect, steps were made to make the sample as representative as possible in sex, age and weight so that a small group can represent a large population.

The relationship between a thermal environment and respondents is dynamic time sampling was considered in addition to subject sampling. Time plays an important role in the adaptive processes in thermal comfort. The adaptive processes of thermal comfort propose that humans respond not only to conditions of specific moments but to the experience of conditions over time leading up to it. There is evidence that people are able to adapt completely within a two week period to a change of temperature (Fergus et al., 2012). Thus, the survey were kept as short as possible and consistent to the collection of data but because time series was needed it was extended to 6 months (Fergus et al., 2012). The TSENS for the study was conducted once a month to avoid serial correlation, difficulty in getting volunteer occupants to respond and reduction in the intrusion into the privacy of selected houses.

Thermal sensation questionnaire was formulated in accordance the ASHRAE RP 884 and was modified to suit the condition in the study area. The questionnaire comprised of biodata, ASHRAE seven-point thermal sensation scale with a pictograph, and the McIntyre thermal preference scale (McIntyre, 1984; EN 15251, 2007; ANSI/ASHRAE 55, 2013; Shahzad et al., 2014). The ASHRAE seven-point thermal sensation scale is subdivided as follows: cold, cool, slightly cool, neutral, slightly warm, warm, and hot (ANSI/ASHRAE, 2013). The McIntyre scale of preference is also divided into warmer, no change and cooler. The pictogragh form of the scale was addeded to improve clarity to person of all literacy levels.

Pre-testing of the questionnaires was carried out in the fourth week of September, 2014. The study was conducted from November 2014 to May 2015. The period of the study captured the six warmest months of November and December 2014, February, March, April and May 2015. The selected months were based on the the climatic data of the Navrongo GMet Weather station from 1970 to 2011 climatology in Figure 3. The period is also falls within the dry season.

The data set for the survey consisted of air temperature, RH, air speed, TSENS and preference votes. The comfort vote and preference votes were taken first and followed by the measuring of environmental variables. The clothing insulation and metabolic rate of the subjects were also recorded based on ASHRAE 2013.

The respondents were to go about their activities as usual as possible during the conduction of the TSENS. Any adaptive option could be explored by the respondents including clothing. According to ANSI/ASHRAE 55-2013 occupants for TSENS survey were to be free to choose and adapt their clothing with insulations ranging from 0.5 to 1.0 clo. However, in tropical conditions studies it could be less as found by researchers like Dhaka et al. (2015). The clothing insulation values were deduced from the clothing table in ASHRAE 55-2013**.** Eventually two and three typical ensemble for males and females respectively were mainly used because that was the dress ensemble used by the respondents. Chair insulation was not used as a survey parameter. Even though an occupant's chair has effect on the heat loss from the body at the area of body-chair contact, it was difficult to estimate because most of the chairs were not standard office chairs. The chairs had back rest and seat in the form of open nets. This made the insulation neglegible.

Before the TSENS and preference voting were conducted, respondents had to be in a near sedentary position for 15 mins. The metabolic rate of the respondents should be between 1 and 1.3 met. This means that they have to either seated quietly, seated and reading seated and writing, seated and typing, or seated and filing. The metabolic rate for each individual for the study was calculated based on the individual's activity after being inactive for 15 minutes from the ANSI/ASHRAE 55-2013.

With a sample size for the survey was 144 occupants (2 respondents for a month from a household) monthly surveys to solicit thermal sensation and preference voting during pre-arranged times to reflect monthly changes in weather were conducted. The respondent had voted on the TSENS and preference scales and afterwards measurement of air temperature, RH and air velocity. An Alnor AVM 440 with articulating probe was used for the measurements at the living zone of a seated person at 0.1 m, 0.6 m and 1.1 m levels in accordance with (ANSI/ASHRAE, 2013). The measurements were taken three times over 30 sec period each at each level.

2.2. Analysis

A response of the TSENS survey collected from the 12 buildings entered into MS excels solver and analysis conducted. Thermal sensation (TSENS) votes distribution was deduced by averaging for the votes of respondents within the range values of (–1, 0 and +1) as representing "satisfied" and (-3, -2, and 2 and 3) representing "dissatisfied."

Also the analysis sought to derive a relationship between environmental parameters on thermal sensation voting patterns and comfort vote. The regression analysis of the thermal sensation with indoor air temperature was done to predict the comfort temperature. The indoor neutral temperature is the observed indoor temperature with a thermal sensation vote equalling zero on the ASHRAE scale. This measure was conducted so that the regression line would predict the neutral temperature without further data treatment that may have modified thermal adaptation and regression.

3. Results and discussions

3.1. Biodata

The respondents who volunteered were 65% males and 35% females. Their mean age was 26.2 years with an age range of 15-60 years. Sixty-five per cent of the respondents responded [where 35% required was required according to ANSI/ASHRAE 55-2013]. The descriptive statistics of height, age, weight are in Table 3.1.

Table 3.1: Biodata of respondents of TSENS

	Mean	St. D	Minimum	Maximum
Height (m)	1.5	0.1	1.3	1.7
Age (y)	26.3	11.9	12	60
Weight (kg)	47.7	11.1	30	90

3.2. Clothing insulation

The clothing ensemble for men were estimated as 0.23, 0.35and 0.39 clo for the study period. For women, the values of 0.47 and 0.50 clo were found to be the frequently used as clothing ensembles.

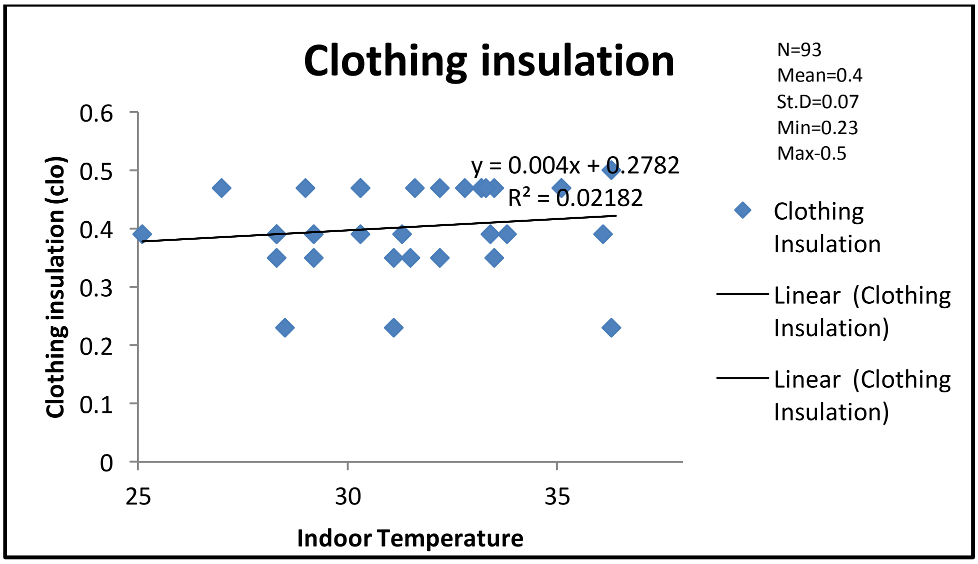


Figure 3.2: Scatter plots of clothing insulation and temperature

From Figure 3.2, clothing insulation is positively correlated to indoor temperature but with a low gradient. This could be as a result of the respondents being well acclimatized to their indoor environment to such levels that the effect of increasing does not affect them. This is different from other studies in regions such as India as studied by Manu et al., 2016 where clothing insulation is inversely correlated to temperature.

3.3. Metabolic rate

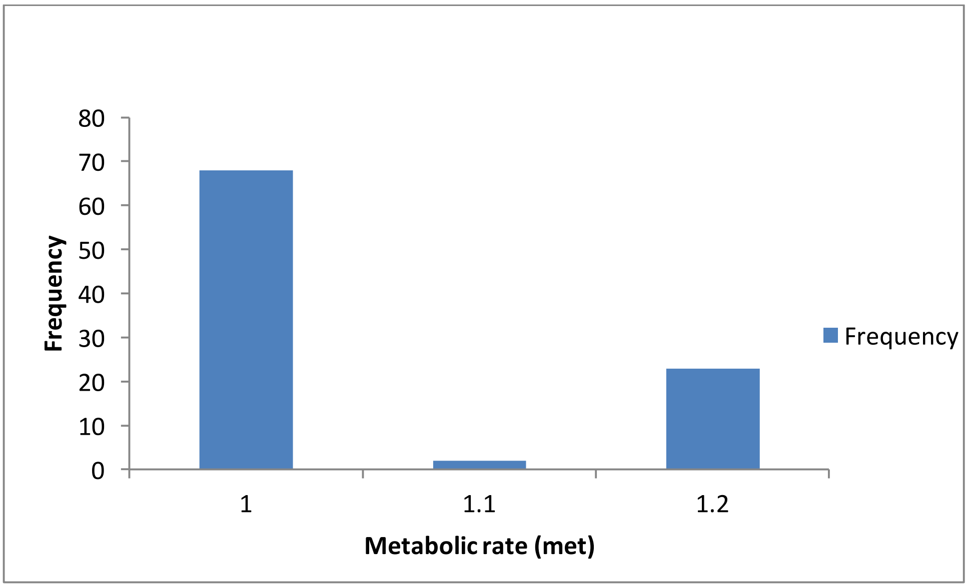


Figure 3.3: Histogram of metabolic rate and temperature

The histogram of the metabolic rate shows that the rate falls between 1.0 and 1.3 met. This is a sufficient condition that the comfort vote is from respondents who are in near sedentary positions in accordance with EN 15251 (2007) and ANSI/ASHRAE 55 (2013).

3.4. Descriptive of indoor air temperature, RH and air speed

The frequency of indoor air temperature for the TSENS in binning of 1k is shown in Figure 3.4. The occupants experience temperature ranging from 29°C to 37°C with 31.7 being the mean.

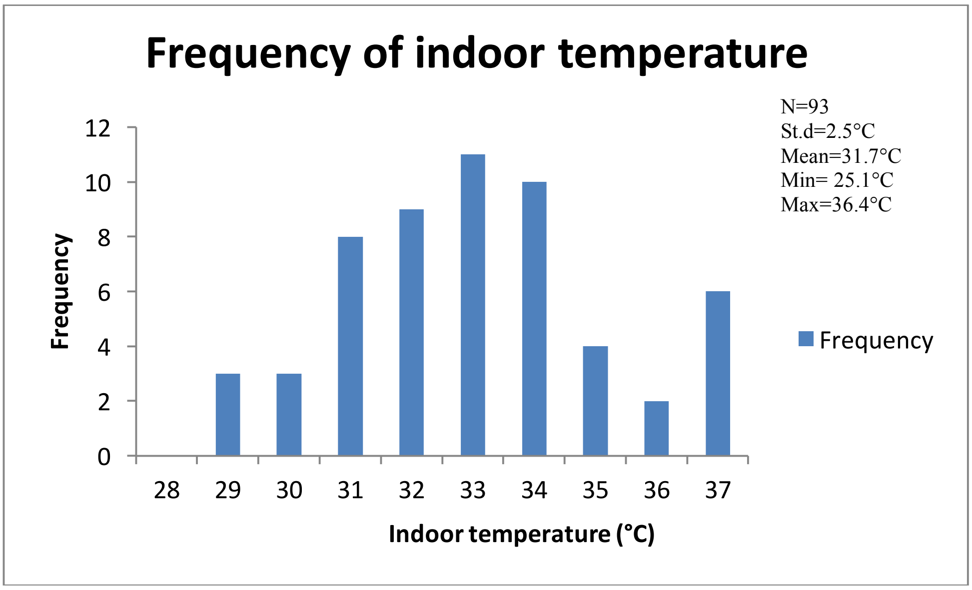


Figure 3.4: Frequencies of indoor temperatures

From Figure 3.5, indoor RH during the TSENS was within the broad range category of (1 to 10%) and (80 to 90%). The minimum RH was 3.3%, maximum 77.2% and average 29.7. The frequencies of the categories below the mean are greater than those above. This gives an indication of the indoor environment was mostly of low humidity during the study.

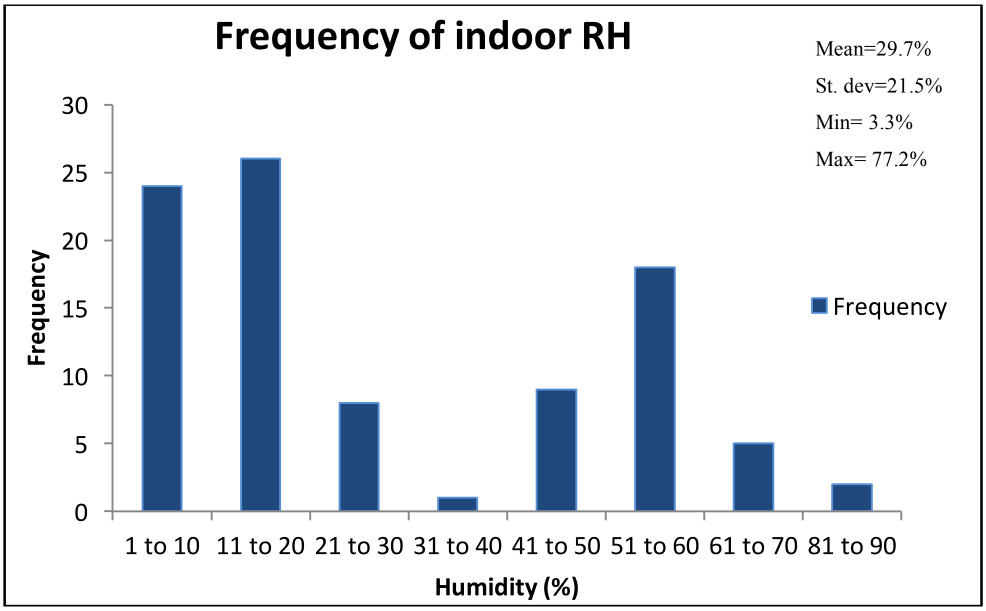


Figure 3.5: Graph of indoor humidity

From Figure 3.6, the range of indoor air speed during the TSENS ranged from 0 to 0.4 m/s. 0.1 m/s. The speed of 0.1 m/s accounted for about 60% of the recorded air speeds. These indicate that air movement indoors were not noticeable because they are below 2.5 m/s according to Auliciem and Szokolay (2007).

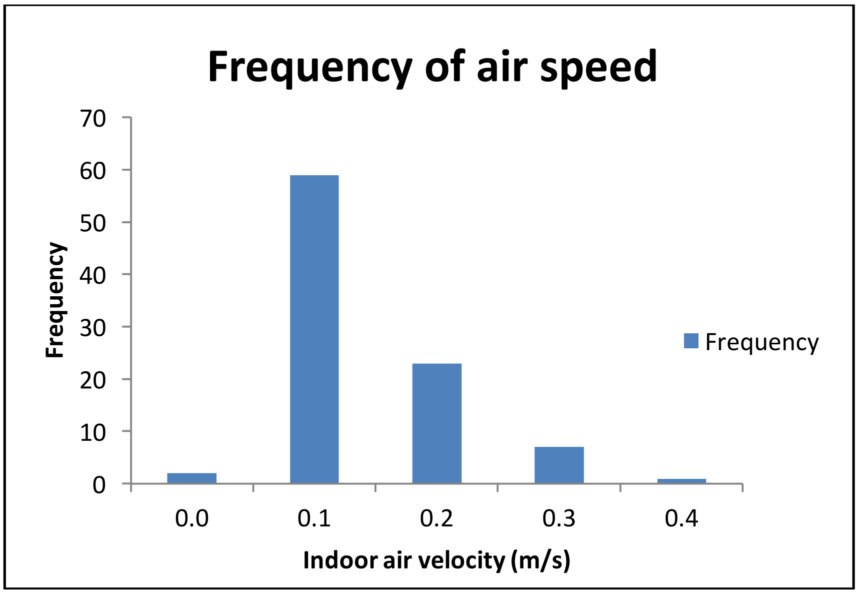


Figure 3.6: Frequency of air velocity during TSENS

3.5. Thermal sensation voting distribution

From Figures 3.7 and 3.8, it was observed that 88% of the respondents found their thermal indoor conditions as acceptable; even though the environment's thermal conditions had least risk of overheating of 45% in a month and 100% in others according to ANSI/ASHRAE 55-2013. This means that the thermal environment is acceptable according to ANSI/ASHRAE Standard 55-2013. No thermal acceptability vote was given, but it was calculated by using the votes within the range of (-1, 0, 1) on the ANSI/ASHRAE TSENS scale. This could mean that such occupants are well adapted and have appreciable level of expectation of such temperature levels. From the Nicol et al. (2009), the respondents voting overheating is (+3, +2) on the

ASHRAE TSENS scale constitute those voting overheating. This constitute 10% of the votes (Nicol et al., 2009).

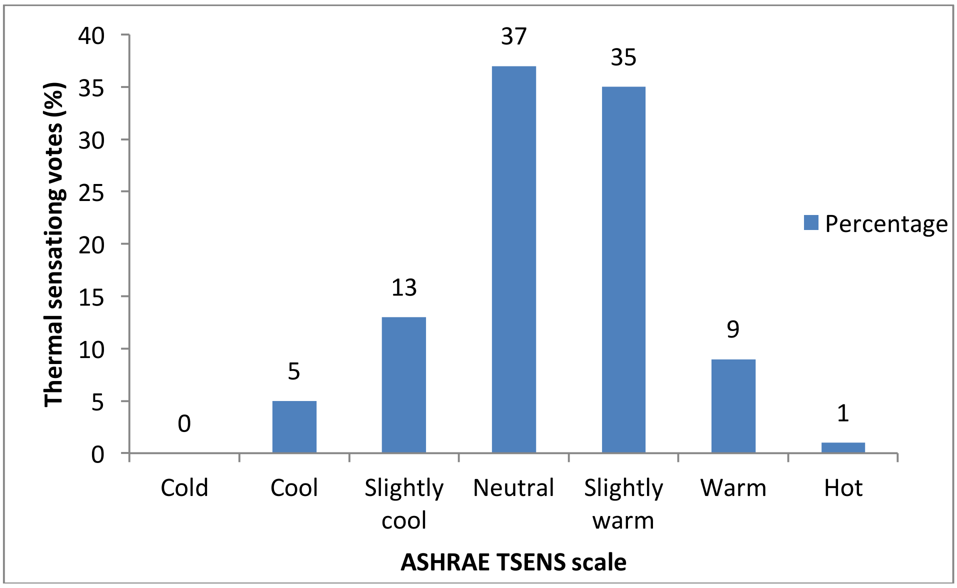


Figure 3.7 Distribution of thermal sensation voting

3.6. Linear regression of thermal sensation vote on indoor air temperature

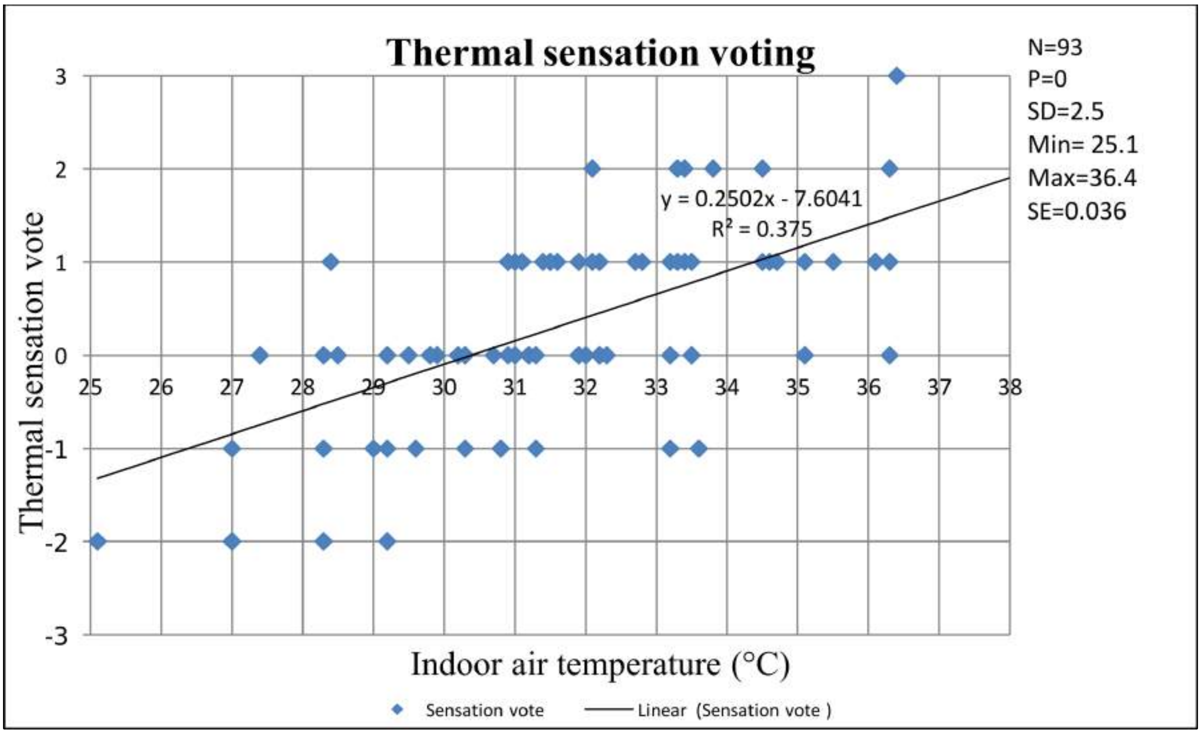


Figure 3.8: Linear regression of thermal sensation vote on indoor air temperature

The linear regression analysis performed using thermal sensation votes (TSV) as a dependent variable against the independent variables of the air temperature is shown in Figure 3.8. The regression equation is;

$$y = 0.2502x - 7.6041 \tag{12}$$

The coefficient of determination, $R^2 = 0.375$. This was achieved with a p-value of 0. The equation of the study closely matches with studies by Karyono (2000) in Indonesia in which the linear regression of air temperature and thermal sensation votes was

$$y = 0.32\,x - 8.43 \quad (13)$$

The coefficient of determination, $R^2 = 0.41$. Katsuno et al. (2012) also derived an equation of from a study among residential buildings in Japan during a summer season.

$$y = 0.403x - 6.937 \quad (14)$$

The neutral temperature of 30.3°C was achieved through linear regression. This was calculated by equalling the regression equation to zero. This predicts the neutral temperature without further data treatment that may have modified thermal adaptation and regression. The neutral temperature closely relates what As result of the difference between neutral and preferred temperature being ± 1 according to Humphreys et al. (2016), the preferred temperature for the study is calculated to be about 29.3°C.

The acceptable temperature (-1, 0, 1 on the ASHRAE scale) range is 25.5°C to 33°C. This was achieved by equalling the linear regression equation to -1 and 1. Eighty-two per cent of the votes were in this range showing that the respondents have adapted to a wide range of temperature. This could also have resulted from the low humidity in the rooms which were mostly below the mean of 29.7%. This agrees with the assertion by Toe and Kubota (2013) that it is easier to adapt to a wide range of temperature when humidity is low. The adaptive options could be an important adaptation process for maintaining comfort at the wide range of temperature. Also it could be that the subjects have adapted to a broader band of indoor temperatures as a result of their long exposure to climate and indoor temperature. This agrees with the adaptive theory of thermal comfort that our thermal expectations and tolerance are defined by one's own thermal experience. These experiences can be the range of temperatures to which the occupant is exposed to especially the most recent (Humphreys et al., 2016).

4. Recommendations

4.1. For future research

There is the need to study the thermal sensation of new occupants alongside old ones with the view to ascertain adaptive actions among occupants.

Existing information on thermal comfort standards such as ASHRAE 55 does not give a true representation of thermal sensation responses in the study area and other tropical regions. There is the need to begin research into a subjective thermal sensation scale for tropical regions. There is also the need to derive adaptive equation for the wider climatic zone.

Also such studies could seek to establish develop legislation on minimum temperature for indoor thermal comfort for advisory purposes.

To increase variation in thermal environment the target accommodation could be residential and office.

References

ANSI/ASHRAE, 2013. *Thermal Environmental Conditions for Human Occupancy*, Atlanta.

Appah-Dankyi, J. & Koranteng, C., 2012. An assessment of thermal comfort in a warm and humid school building at Accra, Ghana. *Advances in Applied Science Research*, 3(1), pp.535–547.

De Dear, R.J. et al., 2013. Progress in thermal comfort research over the last twenty years. *Indoor Air*, 23(6).

Dhaka, S. et al., 2015. Assessment of thermal environmental conditions and quantification of thermal adaptation in naturally ventilated buildings in composite climate of India. *Building and Environment*.

EN 15251, 2007. *EN 15251*,

Fergus, N., Michael, H. & Roaf, S., 2012. Adaptive Thermal Comfort : Principles and Practice. , (April).

Humphreys, M., Nicol, F. & Roaf, S., 2016. *Adaptive Thermal Comfort: Foundation and Analysis* 2016th ed., London and New York: Routledge.

Humphreys, M. & Nicol, J.F., 1970. An investigation into thermal comfort of office workers. *JIHVE*, 38, pp.181–189.

Karyono, T.H., 2000. Report on thermal comfort and building energy studies in Jakarta, Indonesia. *Build Environ*, 35(1), pp.77–90.

Katsuno, J. et al., 2012. Investigation of the comfort temperature and adaptive model in Japanese houses in summer. In *Proceedings of 7th Windsor Conference Windsor Conference*. pp. 12–15.

McIntyre, D.A., 1984. Evaluation of thermal discomfort. In *Indoor Air*. Stockholm, pp. 147–158.

Nicol, F.J. et al., 2009. Suggestion for new approach to overheating diagnostics. *Building Research & Information*, 37(4), pp.348–357.

Nicol, J.F., 1974. An analysis of some observation of thermal comfort in Roorkee, India, Baghdad, Iraq. *Annals of Human Biology*, 1(4), pp.411–426.

Nicol, J.F. et al., 2016. Suggestion for new approach to overheating diagnostics Suggestion for new approach to overheating diagnostics. , 3218(May).

Shahzad, S., Brennan, S. & Theodossopoulos, D., 2014. Individual thermal control in the workplace and changes in thermal preferences in a day: Norwegian cellular vs. Britsh open plan layouts. In F. Nicole, S. Roaf, & L. Brotas, eds. *8th Windsor Conference*. Windsor, UK, p. 1399.

Sharma, M.. & Ali, S., 1986. Tropical Summer Index- a study of thermal comfort in Indian subjects. *Building and Environment*, 21(1), pp.11–24.

Small, L. & Chandler, J.L., 1967. *Thermal comfort study in West Africa*, Kumasi.

Toe, D.H.C. & Kubota, T., 2013. Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot-humid climates using ASHRAE RP-884 database. *Frontiers of Architectural Research*, 2(3).

Webb, C., 1964. Thermal discomfort in a tropical environment. *Nature*, 202(4938), pp.1193–1194.

Defining Thermal Comfort in Desert (Hot-Arid) Climates: A Thermal Comfort Field Survey in Baghdad, Iraq

Saif Rashid[1], Oliver Kornadt[1] and Conrad Voelker[2]

[1] Technical University Kaiserslautern, Department of Building Physics/ Low Energy Buildings, Kaiserslautern, Germany, saif.rashid@bauing.uni-kl.de, oliver.kornadt@bauing.uni-kl.de;
[2] Bauhaus-University Weimar, Department of Building Physics, Weimar, Germany, conrad.voelker@uni-weimar.de

Abstract: Indoor air measurements were conducted in 6 housing units in Baghdad between 2014 and 2016. A deeper look at the measured data showed that air temperatures during spring and autumn complied with the adaptive comfort model. On the other hand, a big variation within the same season was found during winter and summer periods. To verify whether comfort models apply for the climate in Baghdad, a field survey was conducted to define comfort conditions during critical winter and summer periods. The winter survey was conducted in two identical classrooms at the University of Baghdad in December 2016 and January 2017 with 233 responses. The survey was repeated 11 times under 5 different air temperature settings. The survey in summer was a longitudinal survey with 149 responses to evaluate. It was conducted in August 2017; it was repeated 14 times to test the responses under 7 different indoor environmental conditions. The results of the field surveys showed a variation in thermal sensation when compared with the predicted mean vote.

Keywords: Hot-arid climate, thermal acceptance, field survey, extreme conditions, free-running building.

1. Introduction

After decades of war and sanctions, one of the largest challenges facing Iraq nowadays is the electricity crisis. According to (Ministry of Electricity, 2017), the deficit ratio of electricity generation by was about 59% in 2016. This is reflected on daily supply hours, which do not exceed 8 hours per day in extreme summer periods when the demand reaches its peak. 42% of the electricity consumption in Baghdad in 2006 was used for space cooling and 27% was used for heating (Hasan, 2012). These numbers show the need to reconsider the thermal comfort and energy efficiency criteria.

According to Köppen-Geiger climate classification, most of the Iraqi territory lies within the arid climate zone - hot desert climate or hot steppe climate. The mountain area on the north-eastern borders are classified as warm temperate climate with hot summer (Kottek et al., 2006). In most of the regions in Iraq, the climate is characterized by extreme hot and dry summer with maximum daily temperatures between 46-50°C in July and August with large diurnal temperature variation. In winter, the weather is moderate; Temperature only reaches freezing in some nights. The northern moderate climate region has a more moderate summer and snowfall in winter with more precipitation (MoCH Iraq, 2015). With these extreme climate conditions, a high energy consumption is required for cooling or heating the buildings to reach comfortable conditions.

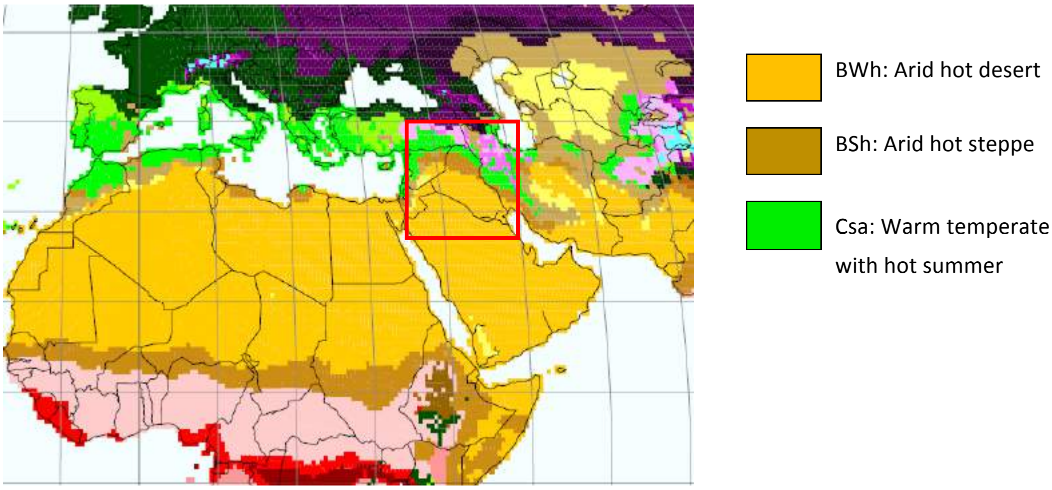


Figure 1: Iraq climate according to Köppen-Geiger classification (Kottek et al., 2006)

In PMV model, information about human activity, clothing, air temperature, radiant temperature, air velocity, and humidity are required to evaluate thermal comfort (Fanger, 1973). According to Humphreys (2006). Using PMV model to predict comfort could lead to unnecessary cooling or heating in warm and cold climates respectively. To check the applicability of comfort models for climate conditions in Iraq, a series of measurements and surveys have been conducted.

2. Online surveys

In 2014, a comprehensive online survey was conducted among a population sample that lives in Iraq. The purpose of the survey was to determine the typical residential buildings (typology, building material, size, location, household, and HVAC) as well as general information about the thermal comfort expectations and preferences in Iraq. Over 600 subjects were invited to fill in the online questionnaire (in Arabic) created using Google form. At the end, 255 person (households) participated. Based on typology, construction year, and material, 6 different residential buildings in Baghdad were selected to measure the air temperature and relative humidity between May 2014 and May 2016, these measurements are discussed in section 3.

In 2017, another online survey was conducted; the goal of this survey was to define the heating and cooling seasons as well as the passive measures implemented during transitional periods (spring and autumn). Participants were asked about the days they used heating or cooling for the first and last time, and about the months they used ceiling fan or had the floor covered with carpet. Results of this survey will be discussed later in section 5.1.

3. Indoor air measurements

The measurements of indoor air temperature, and relative humidity for the selected residential buildings in Baghdad were conducted between May 2014 and May 2016 with different measurement durations ranging from 3 months to 1 year as shown in Table 1. For these housing units, a detailed survey was conducted to get further information about occupancy and seasons.

Table 1 : Empirical measurements: Duration, rooms, and measured parameters

	Unit	Rooms	Start	End	Sensor Type
1	House-1	Living room & Room	Jun 2014	Jun 2015	Air (temperature &RH)
2	Apartment-1	Living room & Bedroom	Jun 2014	Sep 2014	Air (temp. &RH) Surface temperature
3	House-2	Living room, Bedroom & Kitchen	Jun 2015	Jun 2016	Air (temp. &RH)
4	House-3	Living room, Bedroom & Kitchen	Jun 2015	Jun 2016	Air (temp. &RH)
5	House-4	Living room & Room	Jan 2016	Jun 2016	Air (temp. &RH)
6	House-5	Bedroom & Room	Oct 2015	Jun 2016	Air (temp. &RH)

The sensors for indoor air measurements have an accuracy of 0.3°C for air temperature and 2.5% for relative humidity of the measured values in room temperatures 0-40°C (Trotec, 2003). The Sensors were placed on the interior walls at 1.5 – 2 m height.

Measurements conducted in kitchens or empty rooms were not used to evaluate thermal comfort, because of the low occupancy and the conditions during cooking. The rooms are heated with air conditioners or kerosene or electric heaters and cooled with either air conditioners or evaporative coolers or a mix of both depending on the power supply. Knowing that there are hours of blackout and other hours where the rooms were unoccupied, the temperatures presented are only records of instantaneous temperatures rather than comfort temperatures.

The measurements (Figure 8) showed a high variation in air temperature during winter and summer conditions. Consequently, two further comfort field surveys were conducted in December 2016 and August 2017 at university classrooms in Baghdad. The comfort votes collected in these surveys were used to define comfort conditions in winter and summer seasons respectively.

4. Comfort survey

The aim of the comfort survey is to define comfort conditions for buildings in hot arid climates. Its results were compared to different comfort models to define the most suitable model to be used in thermal comfort calculations. Some adjustments may also be needed to be made on the existing widely used models to make these models more accurate for hot-arid climate.

4.1. Previous surveys

Similar surveys were conducted in Baghdad by Webb. However, Webb only collected data form 9 subjects during the summer of 1962. Furthermore, the surveyed subjects were in rooms equipped with only ceiling fans, or with an evaporative cooler in few cases. He reports that individuals living in a hot and dry climate were mostly comfortable at a globe temperature of 32° C during summer (Webb, 1964). However, due to higher living standards that might have changed perception of comfort (Al-Jawadi, 2002), and due to the developments of advanced thermal comfort models, Webb's work can only serve as a starting point for more detailed studies.

It is worth mentioning that similar surveys have been conducted in other countries with similar climate. (Alshaikh, 2016) conducted a long-term survey in Dammam, Saudi

Arabia. As part of ASHRAE's RP-884 the work of (de Dear et al., 1997) included measurements in different climate conditions including warm climates in Pakistan. Comfort conditions in Pakistan were also subject to investigation by (Nicol and Roaf, 1996).

4.2. Survey locations

The winter field survey was conducted in two identical classrooms in the Department of Architecture at the main campus of the University of Baghdad. The classroom capacity was about 60 seats; both classrooms had a floor area of about 135 m² each. The windows of these classrooms face north and equipped with concrete shading louvers, Figure 2. Thus, the effect of solar radiation on the measurements is minimum. Each classroom had a split-unit air-conditioner with 14,36 kW heating capacity.

Figure 2: Winter survey classroom; Interior (left), exterior shading (middle), and ground floor plan (right)

The summer field survey was conducted in a smaller classroom at Al-Nahrain University, College of Medicine in Baghdad. The classroom capacity was about 30 seats, and the floor area was 47 m². The classroom had 2 windows overlooking a courtyard well protected against solar radiation. The air conditioning split-unit has 14,65 kW cooling capacity and the classroom has no ceiling fan as shown in Figure 3.

Figure 3: Summer survey room; interior (left), the courtyard (middle), floor plan (right)

4.3. Measuring instruments

In the field surveys, the four physical indices and the personal conditions required to calculate the predicted mean vote were recorded. External air temperature needed for the adaptive model was collected from the weather station in Baghdad International Airport. Table 2 shows the measured indices, the measuring devices and their accuracy, and the minimum requirements of the ISO 7726:1998.

Table 2: Measurements conducted in the field surveys and the used equipment

Variable	**Control**	**Measurement / Calculation**	**Sensor Type**	**Sensor Accuracy**	**Accuracy ISO 7726**
Outdoor air temperature	×	✓	Weather station		-
Indoor air temperature	✓	✓	NTC	±0,2 K	± 0,5 K
Mean radiant temp.	×	✓	Globe thermometer (Pt100-A)	±0,2 K	± 2,0 K
Air humidity	×	✓	capacitive	±2,5%	± 5,0%
Air velocity	✓*	✓	Anemometer (omni-directional)	±1,0%	0,05+0,05 v_a
Clothing factor	×	✓	Survey + ISO 7730 (estimation)		-
Metabolic rate	×	✓	Survey + ISO 7730 (estimation)		-

* fan setting

For measuring air temperature and relative humidity, sensors were placed in selected points in the classroom so that the distance between each seat and the closest sensor does not exceed 2 metres. The main measurements stand was located at the centre of the classroom. At this location, air temperature and relative humidity were measured at 3 heights as defined in the ISO 7730, globe temperature was measured at 0.10 m and 1.10 m height in winter and at all three heights during summer surveys.

An increase of about 0.1 m/s in air velocity results in a decrease of the predicted mean vote by up to 0.3 (ISO, 2006). Therefore, it is important to get accurate measurements of air velocity. Turbulence caused by differences in air temperature and micro climates of occupants result in a changing air velocity in each point of the room (Voelker et al., 2014). It was technically not possible to measure or calculate air velocity for each point. For winter survey, one portable bi-directional anemometer was used to measure the air velocity at different points during the experiment period.

According to equation [1] from (ASHRAE handbook, 2013), air velocity is inversely proportional to the distance from air outlet. The average air velocity is also affected by the angle between air outlet and selected point, especially when the swing function is used. In that case the seats facing the air outlet have higher air velocities for longer times.

$$\boldsymbol{V_x = \frac{K_c V_0 \sqrt{A_0}}{X}} \qquad [1]$$

Where:

V_x: air velocity at distance x [m/s]

K_c: Centerline velocity constant

V_0: average initial velocity at discharge [m/s]

A_0: area of air outlet [m²]

X: distance to air outlet [m]

During the summer surveys, air velocity was measured using an omni-directional anemometer in 5 different points (blue dots in Figure 3) in the room for the two fan settings used. By running a regression analysis, based on the relation in equation[1], air velocity could was found to be dependent on the distance to the air outlet and the square root of the cosine of the angle to air outlet using the equations [3] and [4] for high fan speed and low fan speed respectively. The coefficients of determination for these regressions were 0.90 and 0.94.

$$V_{air,n+} = 1.32 \cdot \sqrt{\cos(\alpha)} + \frac{1.73}{x} - 1.416 \quad R^2=0.90 \quad [2]$$

$$V_{air,n-} = 0.77 \cdot \sqrt{\cos(\alpha)} + \frac{1.31}{x} - 0.858 \quad R^2=0.94 \quad [3]$$

where:

$V_{air,n+}$: air velocity at the seat no. n with high fan speed

$V_{air,n-}$: air velocity at the seat no. n with low fan speed

x : distance to air outlet

α : angle between air flow and the seat

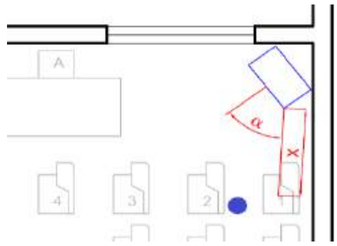


Figure 4: floorplan showing parameters affecting air velocity

4.4. Observations and sample size

The length of each conducted survey was based on lecture duration. During winter surveys, participants were asked to fill the questionnaire about their thermal sensation at the end of each lecture; only the records of the last 30 minutes used in the calculation. During summer surveys, participants filled the questionnaire about thermal sensation at the beginning, middle, and end of the seminar with averaged measured environmental conditions for 30 minutes representing each of these periods (Figure 5). However, measurements were excluded for the times with transient conditions according to ISO 7730.

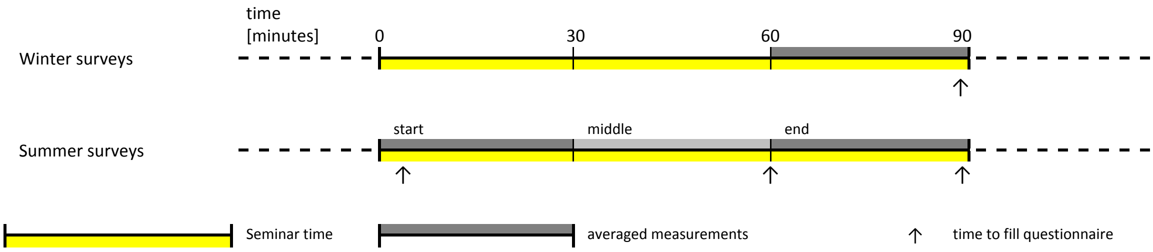


Figure 5: Timeline of seminars and surveys

The winter surveys were conducted during the period between December 20th, 2016 and January 8th, 2017. A total of 134 subjects participated in the survey (combined: longitudinal and transverse) filling 312 questionnaires of which only 223 were complete and evaluable. The survey was repeated 11 times with 5 different temperature settings.

The summer survey was a longitudinal one with 30 participants filling a total of 218 questionnaires with only 117 responses to evaluate. The survey was conducted during the second half of August 2017; it was repeated 17 times (only 14 which matched the steady-state criteria in ISO 7730 were evaluated) to test the responses in 7 different conditions.

Table 3: Summary of the participants during winter and summer surveys

Season	Winter	Summer
Sample size	233	149
(male/female)	(63/170)	(29/120)
Age (years)		
Mean/Standard deviation	20/2.21	23.2/0.73
Maximum/Minimum	33/17	26/22
Clothing insulation (clo)		
Whole sample (male/female)		
Mean	1.17 (1.10/1.19)	0.80 (0.62/0.85)
Standard deviation	0.23 (0.25/0.22)	0.21 (0.15/0.20)
Maximum	1.74 (1.63/1.74)	1.10 (0.94/1.10)
Minimum	0.56 (0.56/0.58)	**0.390.39/0.45)**

5. Results and discussion

5.1. Free-Running or Air-Conditioned Buildings

The Nicol Graph is a simple tool which help to determine how much heating and cooling is needed to reach comfort at certain climates. Equations [4] and [5] show how the comfort temperature is calculated from the average of the monthly mean daily outdoor maximum and minimum temperatures.

$$T_{om} = (T_{omax} + T_{omin})/2 \quad [\ 4]$$

$$T_{comf} = 0.53(T_{om}) + 13.8 \quad [\ 5]$$

where:

Tom: mean of daily outdoor temperature

Tomax monthly mean of daily maximum outdoor temperature

Tomin monthly mean of daily minimum outdoor temperature

Tcomf comfort temperature

According Nicol Graph for Baghdad (Figure 6), comfort conditions can be reached in buildings during summer through passive cooling by using high mass buildings with night cooling. However, active heating is needed during winter; However, 99% of the online survey participants used active cooling and 100% used heating (Rashid et al., 2016).

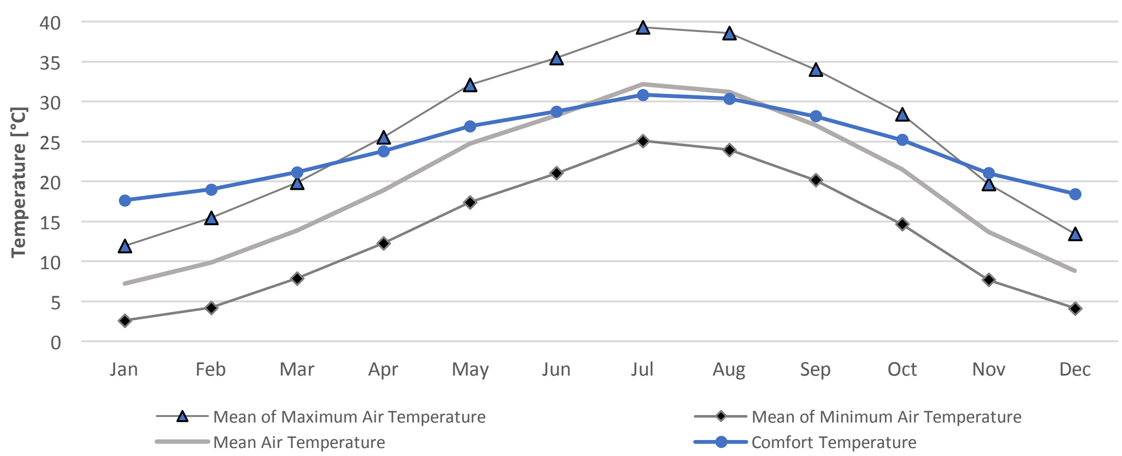


Figure 6: Nicol Graph for Baghdad based on Meteonorm climate data

Figure 7 presents the times of the year where residents would use heating or cooling; it shows that over 50% of the households used heating during December, January, and February. On the other hand, from the beginning of May until the end of September, most households use active cooling. During the rest of the months, comfort is reached by simple adaptive measures such as the use of ceiling fans during warmer days and the use of carpet to reduce the radiative heat exchange during colder periods.

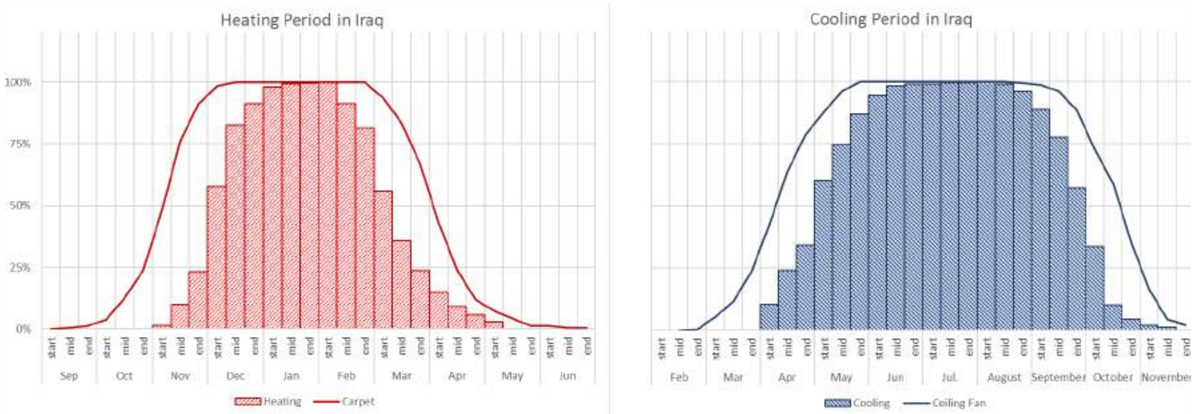


Figure 7: Survey results: periods of using heating (left) and cooling (right)

5.2. Heating and cooling

Since the winter season is relatively short, buildings in Iraq do not have a central heating system like in central and north Europe. In Iraq, most households use portable kerosene, gas, or electric heaters. This kind of heaters does not provide a full control on the indoor climate, because the heaters are designed for a specific heat output which might result in overheating (Piercy et al., 1984).

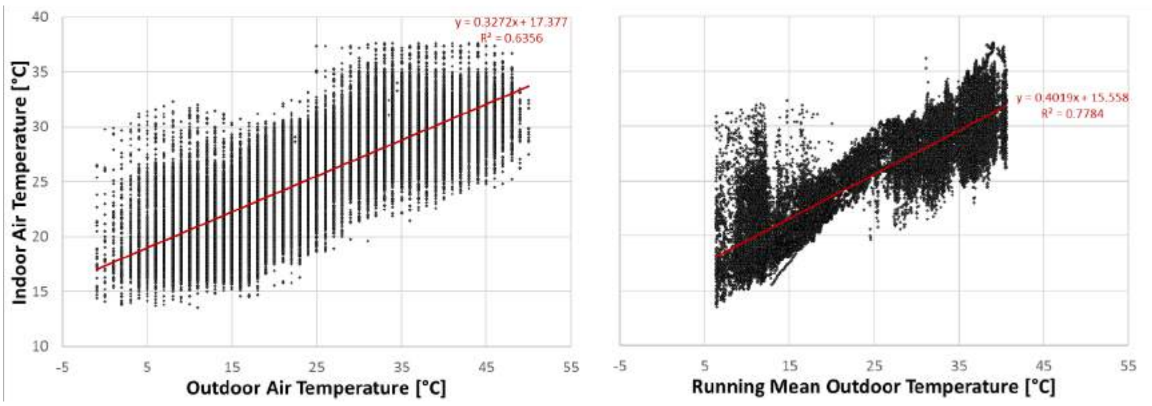
During summer, most households use evaporative coolers which work efficiently in dry climates (Rashid et al., 2016). After the war in 2003, a combination of higher incomes with no taxes increased the market share of air-conditioners, Table 4 shows the survey responses regarding the types of heating and cooling used in the housing units.

Table 4: Survey results: heating and cooling in residential buildings in Iraq

Heating (sample size: n = 253)			**cooling** (sample size: n = 253)		
Air-conditioner	12%		Air-conditioner	35%	
Kerosene heater	25%		Evaporative cooler	12%	
Electric Heate	23%		no cooling (only ceiling fan)	1%	
Gas Heater	1%		mix of several types	53%	
mix of several types	38%				

5.3. Indoor air temperature in residential buildings

The indoor temperature measurements showed a big variation during summer and winter. As shown in Figure 8(a), at an outdoor temperature of 5°C the indoor temperatures ranged between 14°C and 32°C. During summer, the indoor air temperature ranged between 23°C and 37°C when the outdoor temperature was 35°C. This variation can be explained by the blackout hours, as well as the tendency to overheat or overcool during the short supply hours to compensate for the power shortage.



(a) correlation between indoor and outdoor temperatures

(b) correlation between indoor and running mean outdoor temperatures

Figure 8: Temperature cloud for residential buildings in Baghdad

5.4. Adaptive thermal comfort in free running Buildings

For the reasons mentioned in 5.3, the temperature measurements, where heating or cooling is needed, were excluded to eliminate uncertainties. It was assumed that people would react to uncomfortable temperature by turning on heating or cooling. For the free running periods, the plot of indoor temperatures with running mean outdoor temperature was better correlated as shown in Figure 9. The equation [6] of central comfort line for the free running buildings was close to the equation suggested by Nicol et al. (2016) with the 95% inclusion zone being about 5K wide.

$$\boldsymbol{T_{comf} = 0.53T_{rm} + 13.14} \qquad [\ 6]$$

Where:

Tcomf : Comfort air temperature

Trm : Running mean outdoor temperature (7-days)

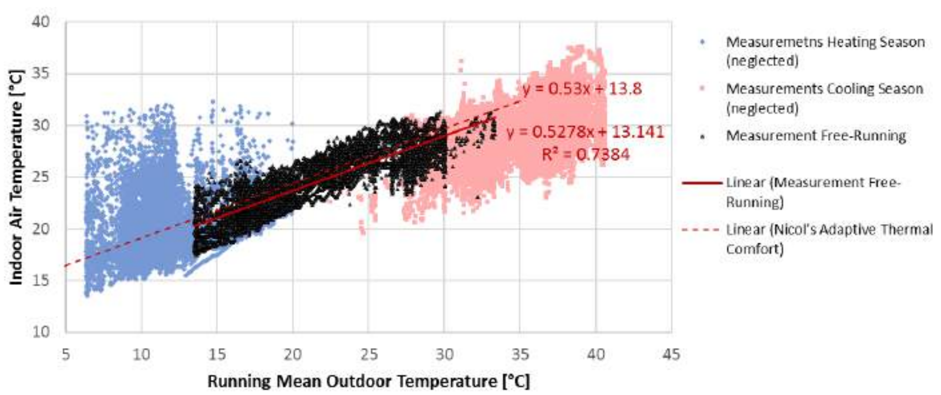


Figure 9: Temperature cloud of free-running residential buildings in Baghdad with regression line of indoor air temperature on running mean outdoor temperature

5.5. Adaptive thermal comfort in air-conditioned buildings

ASHRAE defines acceptable condition when thermal sensation lies between 1 and -1 (de Dear et al., 1997). Figure 10 shows the suggested comfort cloud of those respondents in combination with the comfort cloud of the free running buildings. Most of the measurements for the free-running buildings lied between 13°C and 33°C running outdoor air temperature. There are some gaps in the cloud because the comfort surveys were conducted in extreme conditions.

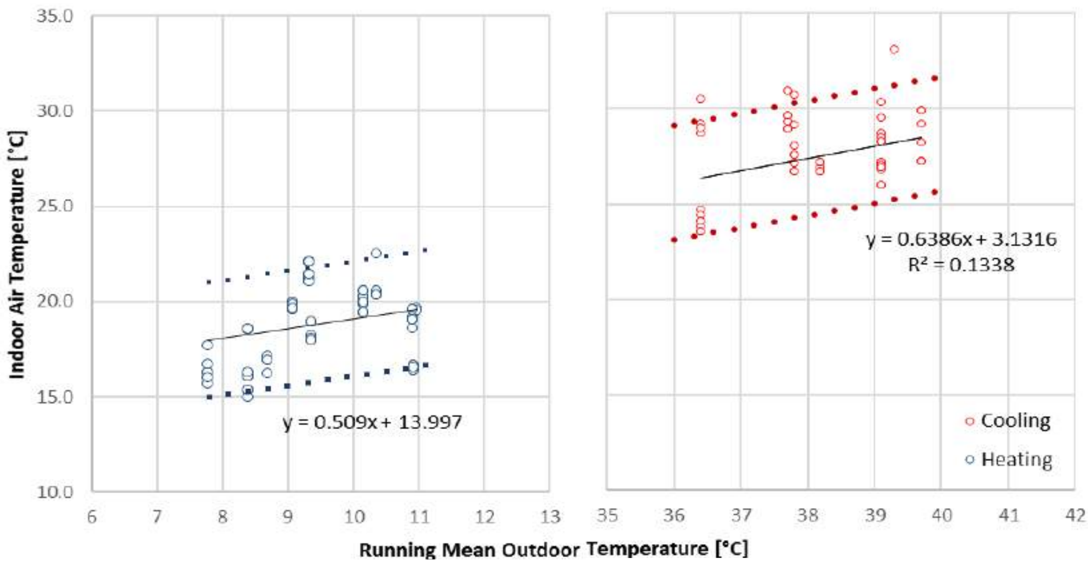


Figure 10: suggested comfort cloud for free-running and air-conditioned buildings in Baghdad

5.6. Cooled buildings in Saudi Arabia

When the results are compared the study conducted by (Alshaikh, 2016) in Dammam, Saudi Arabia, the buildings in Baghdad showed a higher correlation with the outdoor climate. The comfort temperatures defined in Al-Dammam were for the hot season. Comparing these results to the measured temperatures in Baghdad might not be accurate because air temperatures were measured in Baghdad and not the globe temperatures as in Saudi-Arabia. The comfort surveys were conducted in University building making it hard to compare to residential measurements.

Both models look quite different to Alshaikh's model when the whole year is considered. By observing the cooling season only, 95% of the measured temperatures in Baghdad were within the comfort zone defined by Alshaikh with the comfort line being 2K higher for Baghdad (Figure 11).

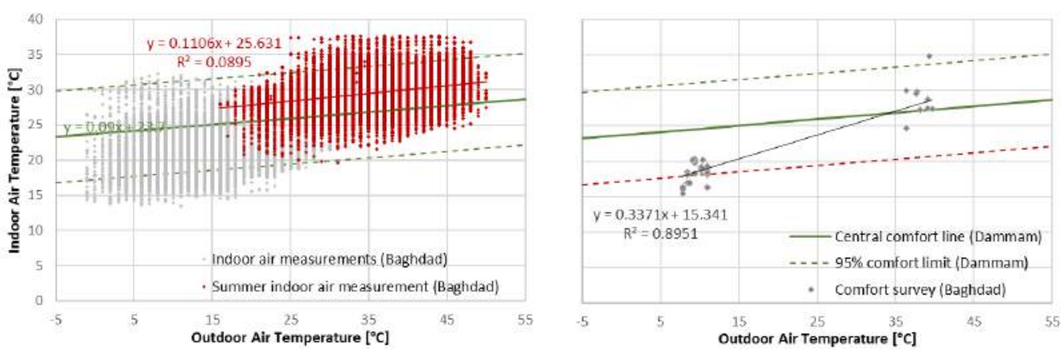


Figure 11: Comparison of Alshaikh's measurements in Al-Dammam to indoor measurements in Baghdad (Left) and comfort survey results (right)

5.7. PMV model in heated and cooled buildings

Predicted mean vote (PMV) was calculated for each response during winter and summer survey based on the measured indices as defined in ISO 7730:2006. The survey responses showed acceptance for colder temperatures during winter and warmer temperatures during summer in comparison to the estimations of the PMV-model. Table 5 shows a summary of the thermal sensation and thermal comfort indices for both surveys.

It is worth mentioning here that since the survey was conducted in a relatively big room, the measurements of the indoor environmental parameters might not be accurate for each seat, especially radiant temperature and air velocity. In addition, the local discomfort conditions are not included in these investigations.

Table 5: Summary of indoor climatic and thermal comfort indices for the field survey in winter and summer

Season	**Winter**	**Summer**
Sample size	233	149
Air temperature (°C)		
Mean / Standard deviation	18.86 / 1.79	30.54 / 3.69
Maximum / Minimum	22.50 / 14.97	36.70 / 23.57
Mean radiant temperature (°C)		
Mean / Standard deviation	18.44 / 1.40	30.87 / 3.59
Maximum / Minimum	20.44 / 15.52	36.23 / 24.69
Relative Humidity (%)		
Mean / Standard deviation	51.58 / 5.49	34.23 / 5.36
Maximum / Minimum	61.46 / 37.97	46.30 / 24.67
Mean air velocity (m/s)		
Mean / Standard deviation	0.17 / 0.28	0.24 / 0.19
Maximum / Minimum	0.4 / 0	0.68 / 0.03
Predicted mean vote		
Mean / Standard deviation	-1.10 / 0.64	1.61 / 1.24
Maximum / Minimum	0.13 / -3.00	3.00/ -1.33
thermal sensation		
Mean / Standard deviation	-0.17 / 0.57	0.80 / 2.08
Maximum / Minimum	1.00 / -3.00	3.00 / -3.00

Figure 12 shows a scatter comparing the average value of calculated predicted mean vote (PMV) to the average of actual mean votes of the participants (AMV) at the same temperatures. Each point in the scatter represents the average of responses of a single survey session. For the winter survey, the average AMV was higher than the average PMV by 0.93 point of the thermal comfort scale. The linear fit of both PMV and AMV is close to being parallel.

The average predicted mean votes are higher than the actual mean vote during summer. The average difference here is about 0.84. However, the difference between PMV and MAV is larger at cooler air temperatures and gets smaller with higher temperatures. These results show that people living in Iraq are more tolerant to colder temperatures in winter and warmer temperatures in summer.

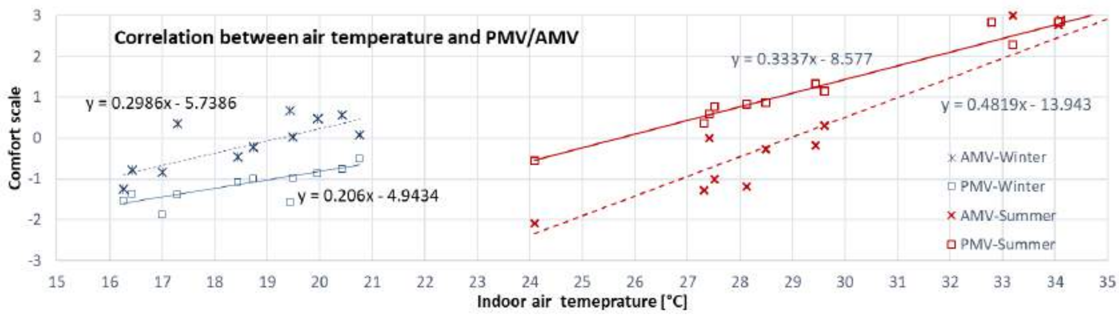
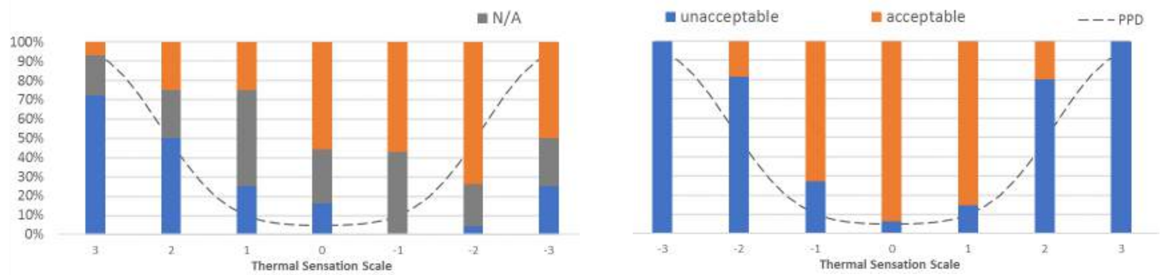


Figure 12: Comparison between predicted mean vote and actual mean vote for the participants in different indoor temperatures during winter and summer

In the field survey questionnaire, participants were also asked whether they found the indoor conditions acceptable. It is noteworthy that during summer, 75% (or more) of the participants with a comfort vote of 2 found it acceptable (Figure 13-a). During winter, the distribution was close to the PPD distribution defined by the ISO-PMV model as shown in Figure 13-b.



(a) summer survey (b) winter survey

Figure 13: Comparison between thermal acceptance and predicted percentage of dissatisfied

5.8. ePMV-Model

Equation **[7]** shows the extended PMV Model. It was developed to predict thermal sensation in free-running buildings in warm climates by multiplying the PMV value by the expectancy factor e (Ole Fanger and Toftum, 2002). A comparison between ePMV and AMV was made even though the summer survey was conducted in a cooled building. Based on results of summer field survey. Equation **[8]** shows the extended PMV model for Iraq; The equation differs from that defined by Fanger and Toftum, it is not only the slope which need to be adjusted by using the expectancy factor, but also the y-intersect.

$$\boldsymbol{ePMV = e \cdot PMV} \quad [7]$$

where

ePMV: extended PMV

e: expectancy factor (e=1.415)

$$\boldsymbol{ePMV = e \cdot PMV + a} \quad [8]$$

where

e: expectancy factor (e=1.415)

a: y-intersect (a=-1.5)

6. Conclusion

The general equation of adaptive thermal comfort can predict comfort temperatures in free running buildings as well as in heated buildings. It is the summer conditions especially in extreme hot days where the results of adaptive comfort model vary from thermal sensation. However, a correlation still exists between neutral temperature and outdoor temperature as the survey results suggest that neutral temperatures are around 19°C and 29°C for winter and summer respectively.

The power supply problem and the simple heating and cooling devices used in Iraq do not provide enough control of indoor conditions which may be the reason why comfort conditions there are not clearly defined. However, the Iraqi code for cooling issued in 2015 is based on the standards defined by ASHRAE.

A long-term study is needed to check the occupants' thermal sensation during different seasons. In such study, it might be enough to monitor the air temperature and relative humidity especially when no comparison with the ISO-PMV model is expected. This study is needed to validate the conducted measurements and surveys and help fill the gaps in the thermal cloud.

Additionally, the perception of thermal scale in Arabic is different than in English. The literal translation for "warm" is "دافئ" which also means "being at a fairly or comfortably high temperature" or to "warm clothing which protect from cold" which clearly has positive meaning especially during winter (Ridha, 1958). On the other hand, the word "cool" cannot be literally translated. Yet, people would like the room to be "cool" or even "cold" during hot summer and "warm" during cold winter days. To investigate this issue, the authors are also participating in an international study addressing the contextual differences in the perception of thermal comfort scales.

7. References

Al-Jawadi, M. (2002) 'Climatic Design Between Traditional and Modern Applications', *the Iraqi Journal for Architecture*, vol. 4, pp. 30–33.

Alshaikh, A. M. (2016) *Design Principles for Thermally Comfortable and Low Energy Homes in the Extreme Hot-Humid Climatic Gulf Region, with reference to Dammam, Saudi Arabia*, PhD, Heriot-Watt University, school of energy, geoscience, infrastructure and society.

(2013) *ASHRAE handbook: Fundamentals*, Atlanta, GA, ASHRAE.

de Dear, R., Brager, G. and Cooper, D. (1997) *Developing an Adaptive Model of Thermal Comfort and Preference: Final Report*.

Fanger, P. O. (1973) *Thermal comfort: Analysis and applications in environmental engineering*, New York, McGraw-Hill.

Hasan, A. A. (2012) 'Available Ways For Energy Conservation in Iraqi Residence Sector. (Arabic)', *Al-Rafidain University College of Sciences Journal*.

ISO (2006) *ISO 7730: Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*.

Kottek, M., Grieser, J., Beck, C., Rudolf, B. and Rubel, F. (2006) 'World Map of the Köppen-Geiger climate classification updated', *Meteorologische Zeitschrift*, vol. 15, no. 3, pp. 259–263.

Ministry of Electricity (2017) *MoE_Annual report 2016*.

MoCH Iraq (2015): *Iraqi Construction Code 404/2*, Baghdad.

Nicol, F. and Roaf, S. (1996) 'Pioneering :new indoor temperature standards" the Pakistan project', *Energy and Buildings*, vol. 23, pp. 169–174.

Ole Fanger, P. and Toftum, J. (2002) 'Extension of the PMV model to non-air-conditioned buildings in warm climates', *Energy and Buildings*, vol. 34, no. 6, pp. 533–536.

Piercy, L. R., Holland, S. S., Holmes, E. S. and Colliver, D. G. (1984) *Agricultural Engineering Energy Series: Kerosene Heaters,* University of Kentucky, College of Agriculture, AEES AEES-35 [Online]. Available at https://uknowledge.uky.edu/aees_reports/4/ ?utm_source=uknowledge.uky.edu%2Faees_reports%2F4&utm_medium=PDF&utm_campaign=PDFCoverPages (Accessed 17 December 2017).

Rashid, S., Kornadt, O. and Voelker, C. (2016) 'Defining Simulation Conditions for Energy-Efficient Residential Buildings in Iraq Using Occupants' Survey and Indoor Climate Measurements', in *YRSB16 Symposium,* Prague.

Ridha, A. (1958) *Dictionary of Language Text (Arabic): a modern lingual encyclopedia*, Beirut, Dar Maktabat Al-Hayat.

Trotec (2003) *TRO-TR-BADL100C Operating Manual* [Online]. Available at https://at.trotec.com/service/services-uebersicht/downloads/bedienungsanleitungen/messgeraete/multifunktion/bedienungsanleitung-datenlogger-dl-100-c/.

Voelker, C., Maempel, S. and Kornadt, O. (2014) 'Measuring the human body's microclimate using a thermal manikin', *Indoor air*, vol. 24, no. 6, pp. 567–579.

Webb, C. G. (1964) *Thermal Discomfort in a Tropical Environment* [Online], Building Research Station. Available at https://books.google.iq/books?id=gZhwcgAACAAJ.

Assessment of transient thermal comfort characteristics in an underground metro station

Kapil Sinha[1] and E. Rajasekar[1]

[1] Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India

Abstract: This paper presents the results of a thermal comfort evaluation of an underground metro station located in a composite climate zone of India (New Delhi). The evaluation comprised real-time monitoring of indoor thermal comfort during winter and summer seasons accompanied by subjective thermal comfort surveys. This study extends the existing field study protocols to transport buildings, which are characterised by dynamic passenger flow. Parameters such as dry bulb temperature (Ti), globe temperature (Tg), relative humidity (RH) and air velocity (Va) were measured using a thermal comfort monitoring system. In addition, spatial variation of Ti, Tg and RH were monitored using lab-assembled Arduino kits. Subjective surveys comprised of transverse responses collected from 360 users and 360 sequential thermal experience responses collected form 60 users. The subjective responses were collected separately for boarding and alighting sequences using an android-based application developed by the team. Transient thermal comfort was estimated using Relative Warmth Index (RWI). A comparative analysis of mean RWI indicates a gradual and uniform change along the alighting sequence of passenger flow. However, the variation of mean RWI is non-uniform and undulated along the boarding sequence. RWI varied from 0.26 at platform to 0.45 at the walkway along the alighting sequence. It varied from 0.3 at concourse to 0.51 at the ticket lobby along the boarding sequence. The neutral temperature (Ti) obtained through thermal sensation vote (TSV) is 30.3°C. The variation in TSV between alighting and boarding passengers were found to be statistically significant at platform, concourse and walkway. A strong positive correlation was obtained between $TSV_{alighting}$ and RWI (R^2=0.52) as well as $TSV_{boarding}$ and RWI (R^2=0.53). An RWI value of 0.14 corresponded with mean neutral TSV for the alighting sequence while it was 0.33 for the boarding sequence. The passengers exhibited higher level of tolerance to heat discomfort than that predicted by RWI. Acceptable thermal limits along the alighting and boarding sequence of the metro station are presented.

Keywords: Thermal comfort, Relative warmth index, underground metro, sequential survey

1. Introduction

Expanding cities and growing population are leading to immense pressure on the mobility infrastructure. According to World Bank data (World Bank, 2017) annual urban population growth for the year 2016 was recorded 2.3%, and by 2050, the urban area of India will witness the addition of 300 million residents. With the development of urban areas and an increase in population, there is an urgent need of shift from private transportation to the mass transportation such as buses, metro rails and mono rails. Metro networks in India is widely acceptable means of transportation, since it is not affected by the traffic congestions. Since metro rails are used by a large number of people because of its high speed and congestion free transportation, metro stations are one of the busiest and high density public buildings. Despite being used for the very short duration of time; metro station houses a huge number of passengers within an enclosed space. This can cause an adverse effect on health due to uncomfortable thermal conditions, air quality and lack of proper ventilation (Al horr *et al.*, 2016). Apart from these Metro stations have high internal heat gains. These heat sources are so prevalent that in summer it may lead to high degree of passenger discomfort if the metro stations are not appropriately cooled (Ampofo et al, 2004a). In an underground station, a comfortable thermal environment is one essential criterion, and it comes with high energy requirement. Air conditioning systems in the metro station are responsible for around 40% of electricity consumed in metro stations (Wang et al., 2013). Understanding of occupant thermal perception and expectation is a step towards improving the user experience at optimal energy consumption.

1.1. Need for study

Metro station is characterised by fluctuating occupancy rates and variable activity levels. Apart from this, users of a metro station are subjected to transient environment with varying enclosure geometry and surface characteristics. In terms of thermal comfort, this makes the metro stations distinct from other public buildings which have near-static conditions. Despite being used for a short duration of time; it has a significant impact on overall comfort in the journey. Thermal comfort studies available in the literature are mainly focussed on steady state conditions with almost static environment and personal parameters. There are limited research studies conducted for the building like Metro Stations (Katavoutas *et al.*, 2016), (Abbaspour *et al.*, 2008), (Ye *et al.*, 2010) and (Han, Kwon and Chun, 2016). The complexity involved in defining the acceptable thermal comfort criterion for underground metro stations has been discussed in the article by (Ampofo *et al.*, 2004a).

1.2. Learning from past thermal comfort studies

Characteristics of Metro stations makes it different from other buildings such as office building and residential apartments. One of the most important phenomena in the station is rapidly fluctuating occupancy level and activity level ranging from waiting at a ticket counter (met value: 1.6) to ascending a staircase (met value: 8). This complex environment inside the metro stations, which is modulated by passenger behaviour, plays a vital role in determining thermal comfort. It poses a challenge in the development of a standard criterion for thermal comfort assessment in such spaces.

Recent studies on thermal comfort in the underground station environment have used a range of indices. Research review by (Ampofo *et al.*, 2004b) presents a thorough analysis of deferent indices for underground stations application. The study conducted in Shanghai Metro stations by Ye *et al.*, 2010, presents the use of operative temperature (T_{op}) for determining relationship between thermal comfort and indoor temperature. Han, et al, 2016, uses standard effective temperature (SET*) for determining percentage of uncomfortable passengers in the study conducted in subway stations of Seoul. This study was accompanied by the transverse passenger survey. In the recent study conducted in the Athens Metro stations by Katavoutas et al, 2016, thermal comfort was estimated using the PMV (predictive mean vote and the PPD (predictive percentage dissatisfied) scales as proposed by ISO-7730 (2005). The PMV-PPD scales have been also used in the past studies by (Marzouk and Abdelaty, 2014), (Khalil and El-Bialy, 2012) and (Ordódy, 2000).

Since most of the indices did not adequately characterise the transient aspects including all variables needed to predict thermal comfort for subway environments, two indices, the Relative warmth index (RWI) and Heat Deficit Rate (HDR) were developed for the *Subway Environmental Design Handbook*, 1976. Thermal comfort study conducted by Abbaspour *et al.*, 2008, in metro stations and carriages of Tehran metro comprised of field measurements in two different seasons. The results were analysed using relative warmth index (RWI).

The paper has the following objectives (a) evaluation of thermal characteristics of indoor environment and passenger perception in the underground metro station; (b) To study the relevance of survey techniques in determining thermal comfort for transient application. (c) Evaluation of the neutral temperature for occupants in the underground metro station and (d) To establish relationship between calculated(RWI) and observed(TSV) thermal comfort.

2. Details of the Study

There are presently eight metro rail systems operational in India. New Delhi has one of the longest networks with fully operational underground stations. The study has been carried out in Hauz Khas Metro Station of New Delhi Metro which is one of the busiest underground system. The metro station is noted for the serving a wide category of passengers with an average ridership of around 32,836 passengers per day. Hauz Khas station is located in an institutional cum commercial land use and shows two peak hours i.e. Morning and Evening peak.

As per Koppen climate classification, New Delhi is monsoon influenced humid subtropical zone having high variation between summer and winter temperatures and precipitation. While the National Building Code of India defines New Delhi under Composite Climate. The city experiences the diversities of all the major season of summer, winter and monsoon. The city experiences extreme heat during summer which ranges from early April to June and extreme cold in winter from December to January. New Delhi has average temperature of *42°C* during the summer and *6°C* during winter.

Hauz Khas metro station is operational since 2010. As per the metro classification, Hauz Khas Station has centrally paid concourse with two opposite unpaid areas and Island type platform. As shown in Figure 1, the station has three layers – (i) entrance which is located on the ground level (±0m), (ii) the concourse and ticket lobby in the middle layer (-6.5m) and (iii) the platform on the bottom layer (-11m). The metro station has a platform width of 12 m and length of 180 m, which can accommodate an eight-coach metro train. It has a centrally located concourse of width 16 m and length 110 m. Two ticket Lobbies with floor area of around 540 sq.m. are located on either side of the concourse. The station has two arms approaching directly into ticket lobby for entering the station from ground level. The walkway width varies from 6 m to 6.5 m. The platform and concourse area are air-conditioned using constant air volume air conditioning system with water-cooled chillers.

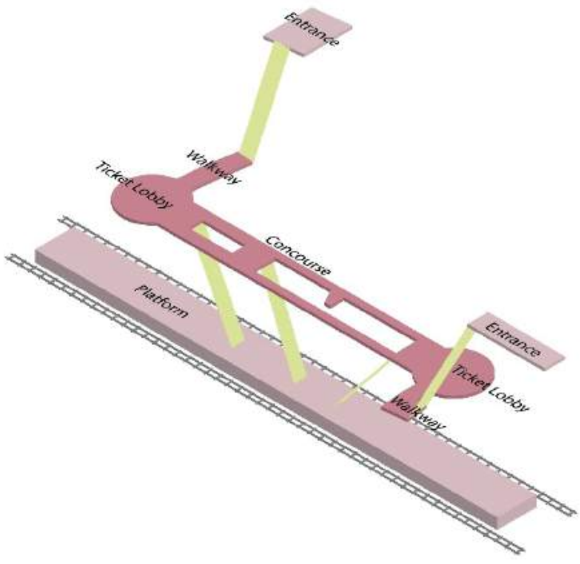


Figure 1 Space diagram of metro station

For the purpose of this study, the spaces are categorised into four zones defined by their spatial character, surrounding geometry, passengers' activities, metabolic rates and environmental conditions to study the possible influence on the thermal characteristics. The four-building zone identified for the study are Platform(PF), Concourse(CC), Ticket Lobby(TL) and Walkway(WW). Along with this two-interface zone are identified i.e. Outdoor(OD) and Carriage (CR).Figure 2 denotes the above zones in the metro station.

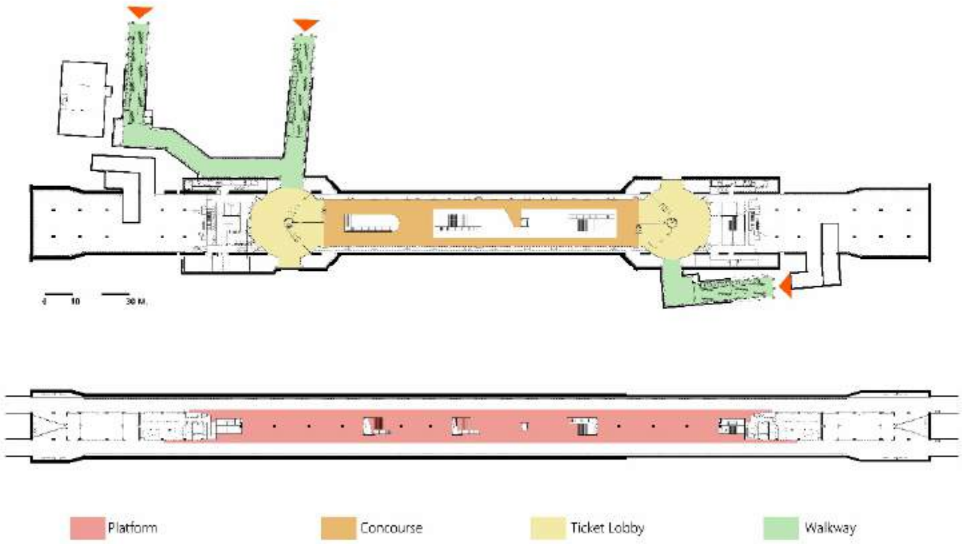


Figure 2 Identified zones in the metro station floor plan

The study was carried out in two different seasons to understand the seasonal influences on thermal characteristics. The winter measurements were undertaken during January and summer measurements during May. The timing of the study was placed such that the two peak hours (morning and evening) and one off-peak hour of the station are covered.

3. Methodology

Figure 3 presents the flow chart of research methodology used in this study.

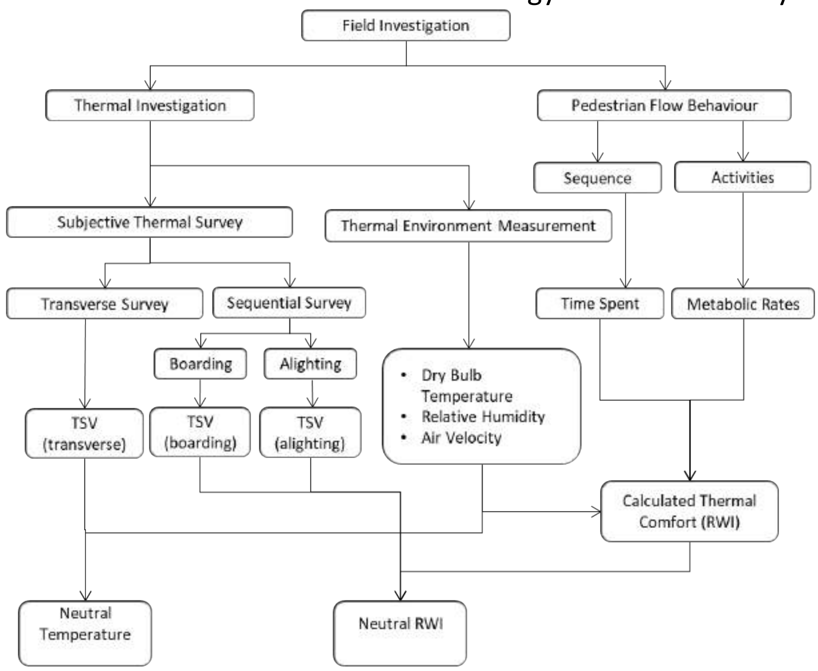


Figure 3 : Flow Chart of research methodology

3.1. Thermal Environment Measurement

The environmental variables were measured at the four zones i.e., walkway, ticket lobby, concourse and platform. Apart from this, measurements were carried out in outdoors (near entry and exit locations) as well as inside the metro carriage during the train operation. The parameters measured during the study are dry bulb temperature (Ti), globe temperature (Tg), relative humidity (RH) and air velocity (Va). Dry bulb temperature (Ti) and relative humidity (RH) were recorded continuously at all the zones for the period of the study while globe temperature(Tg) and air velocity (Va) were measured only during the survey.

Six sets of Arduino based data-loggers (fig. 4) were developed and fabricated for the purpose of this study. This data logger is equipped with Ti (thermistor: -40 to 80°C, ±0.5°C accuracy) and RH (0-100%, 5% accuracy) sensors. The data logger was developed on an Arduino UNO board with a battery backup sufficient for continuous daylong monitoring at a logging interval of 15 seconds. All the data loggers were tested together under the same environment conditions and cross-calibrated in the laboratory with a class I Delta Ohm HD32.3 comfort meter.

Figure 4 Arduino based data-loggers

Apart from the above loggers, a thermal comfort logging station (Delta Ohm HD32.3) was deployed during the study. The station consisted of Ti, RH, Tg and air velocity probes (hot-wire anemometer sensor). The instrument was mounted 1.1m above the floor level in indoor conditions and 1.7 m from ground in outdoor condition (Nakano *et al.*, 2005). The instrument was protected from direct solar radiation during outdoor deployment. This station recorded the environmental variables for one-hour duration at each of the identified zones during peak as well as off-peak slots.

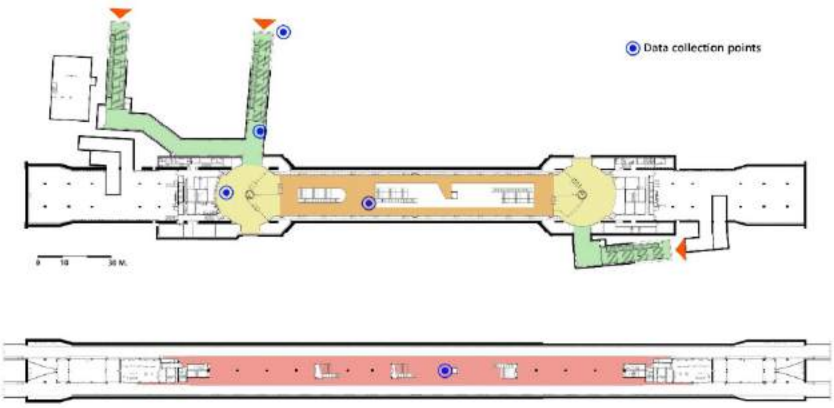


Figure 5 Plan showing location of Thermal comfort meter setup

Figure 6 Thermal comfort meter setup at (A)platform and (B) ticket counter

3.2. Subjective Thermal Survey

Subjective thermal surveys were administered along with the physical measurements in order to assess perceived thermal comfort at the various zones of the metro station. Han, et.al, 2016 carried out thermal comfort assessment in Seoul metro stations and highlights the special considerations for subjective assessment in transitional stations which are occupied only for short period of time. Based on the inferences from literature review two types of subjective assessments i.e. transverse survey and sequential surveys, were carried out.

Using the elementary statistics, it was found that for a 95% confidence level and margin of error being 6% the recommended sample size is 265 for the population of 32,836. With the same confidence interval and margin of error of 5%, the recommended sample was 380. In this study 360 samples were studied. All these sample were collected using stratified sampling based on the pilot study.

Transverse responses were collected using pen-paper based survey. For this purpose, five-point survey questionnaire was designed based on the ISO 10551, which intends opinions of passengers about their Thermal Perception, Affective Assessment, Thermal Preference, Personal Acceptability and Personal Tolerance of the thermal condition to which they are exposed at the spot of the survey. For this survey, 30 random samples were chosen at the stations for every zone. A total of 360 subjects filled the responses at different time slots. Since the passenger were moving, the survey responses were collected on the go along their movement.

Sequential surveys were administered in order to assess the passenger response during their boarding and alighting sequence. These were carried out using an android based form that was developed by the authors. The form is developed on open source program ODK (Open Data Kit). The questionnaire consists of a 7-point ASHRAE scale for the comfort rating and 5-point Scale for the Affective Assessment. The subjects were given a tablet/smart phone with the questionnaire application. The registered their responses during the activity timeline and responses at each spot was stored on the device with the time stamp. The responses were transmitted to the cloud server. Two different forms were developed for the Boarding and Alighting sequence since the activity sequences and transit spaces are different in both the cases. The main objective of the sequential survey was to replicate the way boarding and alighting sequence took place in the metro station. Each respondent completed the survey for both the questionnaires during the same time slot. This survey was carried for three days each in summer and winter. A total of 360 samples was collected for both sequences.

3.3. Thermal Comfort Indices

Metro stations are characterised by drifting activity levels at different zones with predominantly transitional and short-term occupancy rates. Therefore, there is need for an index, which can support non-steady metabolic condition, and takes consideration of exposure time. Based on a review of available indices, Relative Warmth Index (RWI) was chosen for thermal comfort assessment in this context.

RWI is was developed by Lee and Henschel based on Relative strain index, especially for transient or metro environment application (*Subway Environmental Design Handbook*, 1976). Relative strain index is the ratio of the actual amount of sweating required to the maximum sustainable amount of sweating. Since this index was not indicating the thermal comfort, it was not suitable for the metro environment. RWI was proposed by the Transportation Air Conditioning Committee of American Society of Heating, Refrigerating and Air- Conditioning Engineers (ASHRAE)(Patania *et al.*, 2012). For the application in warm environments, the theory of Relative Strain Index was used to evaluate RWI, while for the cold environment, the concept of RSI was used to derive another index called Heat Deficit Rate (HDR).

RWI is a function of various environmental factors, personal factors and also the exposure time. Unlike PMV-PPD which considers a constant metabolic rates and clothing levels in their prediction, RWI can predict the thermal sensation even when metabolic rate is changing with the time. This makes RWI more suitable for the metro environment. Following are the expressions for the RWI

$$RWI = \frac{M(I_{cw} + I_{a)} + 1.13(t - 95) + R.I_a}{70(1.73 - P)}$$

when P > 0.67 in of Hg

$$RWI = \frac{M(I_{cw} + I_{a)} + 1.13(t - 95) + R.I_a}{74.2}$$

when P <= 0.67 in of Hg

where

- M=Metabolic Rate, Btu per (hr)(sq.ft.)
- I_{cw}=Insulation of clothing based on wet cloth assumption, clo
- I_a=Insulation effect of c=air boundary layer, clo
- t=dry bulb temperature, F
- P= vapour pressure of water in air

The average oxygen consumption takes about 6 minutes and therefore it is assumed that transition in metabolic activities also takes 6 minutes. For determining non steady state metabolic activity, it can be calculated by linear interpolation (*Subway Environmental Design Handbook V1*. Second, 1976).

$$M_T = M_I - \frac{T}{6}(M_I - M_F)$$

where

- M_T=Metabolic Rate at lapsed time T, Btu/ (hr)(sq.ft.)
- M_I =Initial Metabolic Rate, Btu/ (hr)(sq.ft.)
- M_F =Final Metabolic Rate, Btu/ (hr)(sq.ft.)
- T=Lapsed time, min

For the transient condition in the metro station, Value of clothing insulation also changes with the activity levels and hence have six-minute assumption in metabolic rates. For determining Insulation of clothing at changing metabolic activity following expression is used.

$$Icw_T = Icw_I - \frac{T}{6}(Icw_I - Icw_F)$$

4. Results

4.1. Indoor thermal characteristics

The box and whisker plot of the dry bulb temperature and relative humidity at different zones during summer are presented in Figure 7. The dry bulb temperature at the platform was higher than all zones in both the seasons. The mean dry bulb temperature monitored during the study were 31.3°C in the walkway(WW), 29.2°C in the ticket lobby(TL), 31.2°C in the concourse(CC) and 33.6°C, while the outdoor(OD) mean was 38.3°C. One-way ANOVA test to compare the dry bulb temperature at various zone shows significant differences of temperature among the zones. It was found that the mean difference between Walkway(WW) to Outdoor (7^{o}C) and Carriage(CR) to Platform (8.8^{o}C) is significantly high. Relative humidity variations found to be minimal throughout the indoor spaces. Platform has the highest humidity levels. Relative humidity monitored throughout the study shows RH level below 50% at all the zones and the mean relative humidity ranges from 40.2% in concourse to 35.2% in platform. The walkway zone shows a high deviation in relative humidity with a standard deviation of 6% throughout the operational hours.

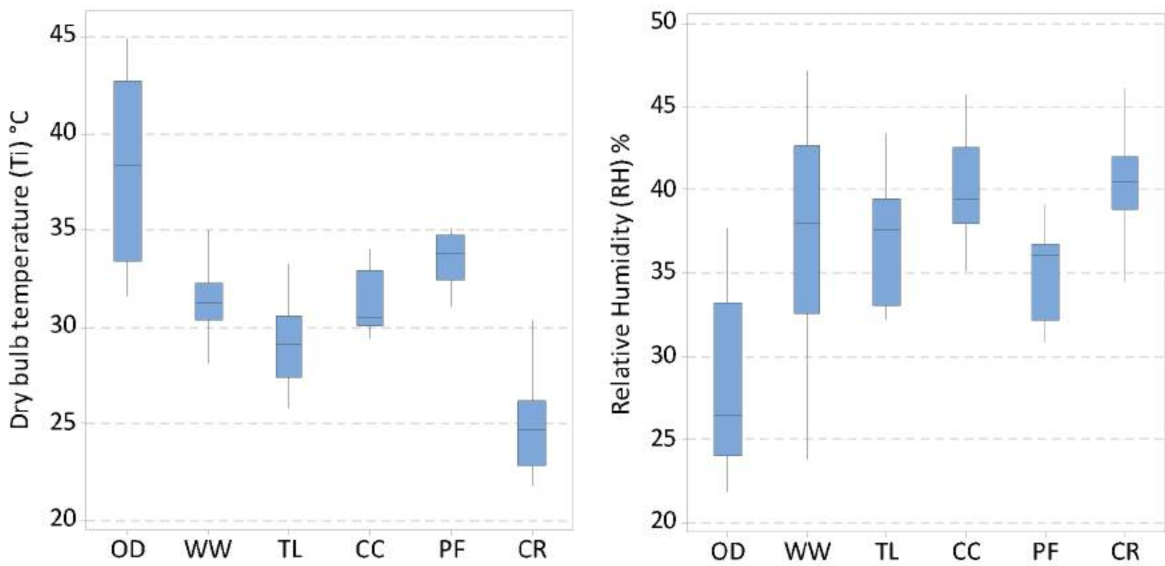


Figure 7 Dry bulb temperature and relative humidity at different zone of metro station

Figure 8 illustrates the distribution of air velocity and wet bulb globe temperature(WBGT) at different zones of the metro station. The mean air velocity in the station was 1.1 m/sec. The air velocity at the walkway was slightly higher (1.6 m/sec) compared to the other zones.

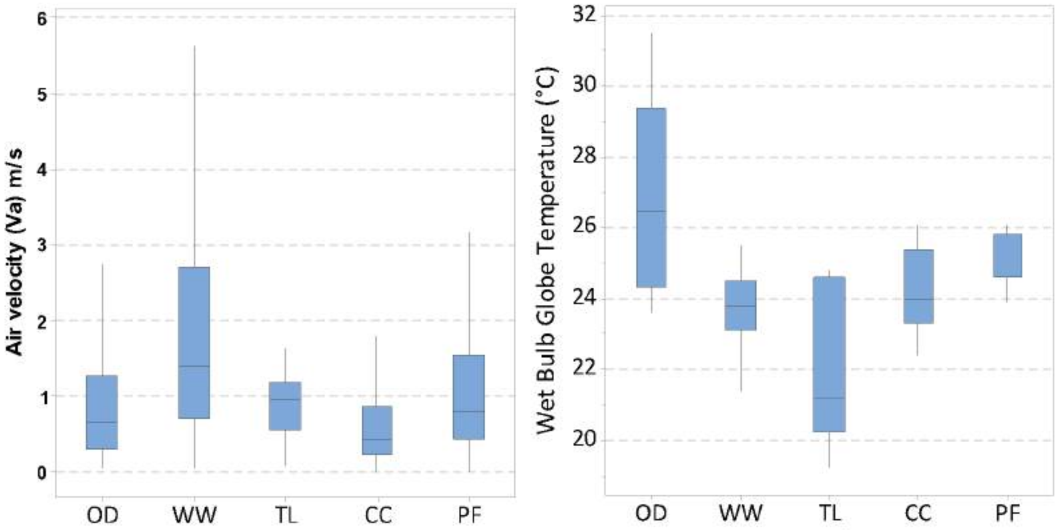


Figure 8 Air velocity and wet bulb globe temperature at different zones of metro station

The mean WBGT was found to be 23.8°C. Platform zone has maximum WBGT of 25.4°C while Ticket Lobby observed the least WBGT of 21.9°C. The variation of WBGT between the various zones were found to be statistically significant.

RWI was calculated using the environmental parameters collected during the field study. The study conducted in Tehran metro by Abbaspour *et al.*, 2008 had calculated RWI using some standards parameters for the time spent. For this study, time of exposure was recorded as a part of sequential surveys. The passengers were asked to respond on the entry and exit of particular zone for the time of exposure. Table 1 presents the details associated with RWI computation.

Table 1: Key values for the calculation of RWI for this study

		Time Spent(min.)**[t]**	**Meabolic Rate** Btu per (hr.)(sq.ft.) **[M]**			**Clothing Insulation**(Clo)**Wet Cloth Assumption[Icw]**			**Activity Induced Velocity** (fpm)	**Mean Incident Radiant Heat** Btu per (hr.)(sq.ft.)**[R]**
			Meabolic Rate(Intial)	**Meabolic Rate(Final)**	**Metabolic Rate(Calculated)**	**Clothing (Initial)**	**Clothing (Final)**	**Clothing Calculated**		
Boarding Sequence	**Outdoor**	3	71	54	62.5	0.3	0.35	0.33	400	10
	Walkaway+ Stairs	1.67	54	74	59.56	0.35	0.3	0.34	300	0
	Ticket Lobby	1.16	74	31	65.72	0.3	0.5	0.34	30	0
	Concourse+Stairs	0.86	31	74	37.16	0.5	0.3	0.47	200	0
	Platform	3.42	74	39	54.07	0.3	0.4	0.36	100	0
	Carriage	6	39	22	22.00	0.4	0.5	0.50	30	0
Alighting Sequence	**Carriage**	6	22	22	22.00	0.5	0.5	0.50	30	0
	Platform	1.63	22	39	26.63	0.5	0.4	0.47	100	0
	Concourse+Stairs	0.86	39	72.83	43.85	0.4	0.3	0.39	200	0
	Ticket Lobby	1.16	72.83	71	72.48	0.3	0.3	0.30	30	0
	Walkaway+Esclato	1.67	71	72.83	71.51	0.3	0.35	0.31	300	0
	Outdoor	3	72.83	54	63.42	0.35	0.35	0.35	400	10

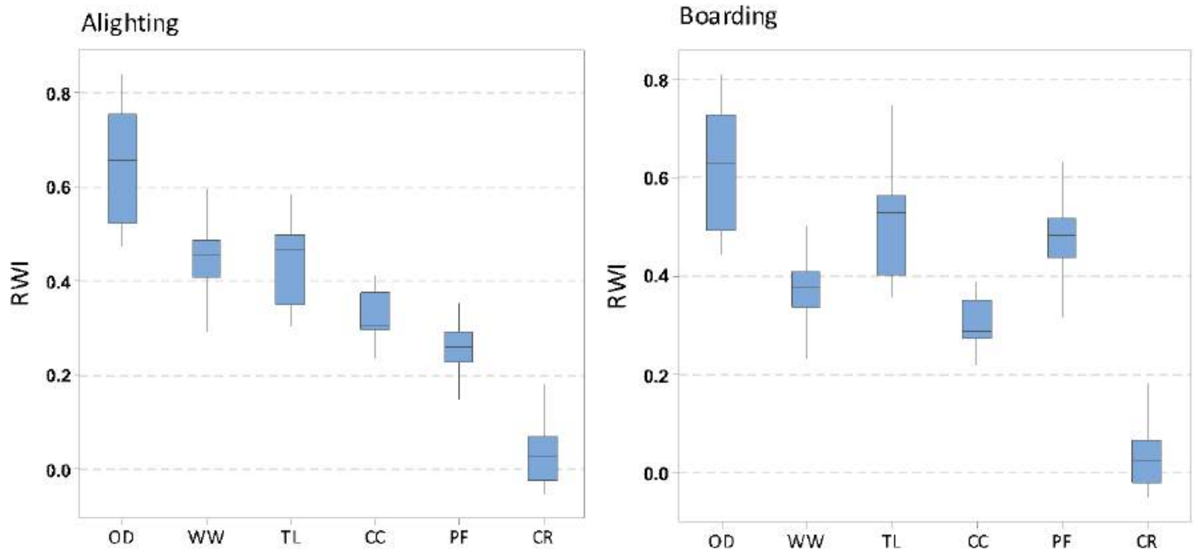


Figure 9 RWI during alighting and boarding sequences

Transient thermal comfort estimated using the RWI during and alighting and boarding sequences are shown in Figure 9. Since sequence of activities and their corresponding metabolic rates are different for the alighting and boarding sequences, different RWI was calculated for their respective locations based on the sequences. It was found that the alighting sequence i.e. from carriage to the outdoor, was gradual and change during sequence of journey was uniform throughout. During the alighting sequence, mean RWI was found to be 0.36 which corresponds to Hot as per ASHRAE comfort classification. During the alighting sequence the mean RWI varies from 0.26 at platform to 0.44 at the walkway. Whereas Boarding sequence, i.e. from outdoor to carriage shows undulated and non-uniform RWI throughout the journey. The mean RWI for boarding sequence was found to be 0.41 which also corresponds to Hot as per comfort classification. The mean RWI during boarding sequence at different locations were 0.37 at walkway, 0.50 at ticket lobby, 0.29 at concourse and 0.48 at the platform. However, it was found that in both sequences, the shift in RWI between the indoor and outdoor environment is significant. Similarly, the shift in RWI between the indoor environment and carriage is significant. Such rapid changes are indicative of possible thermal stress.

On comparing the mean of RWI of both the sequence at the same location using independent sample T-test, it was found that Platform zone has a significant difference in RWI with respect to the boarding (mean RWI= 0.48) and alighting (mean RWI=0.26). However, no significant difference was found between RWI of other zones for boarding as well as alighting sequences.

4.2. Passengers' thermal comfort evaluation

Figure 10 illustrates the thermal perception of passenger at different zones during the summer and winter. There is a non-uniformity in thermal perception across different zones during the summer. But during winter the perception across locations is more uniform in nature except at the platform. Preliminary statistical tests were conducted to explore the data. Friedman test indicated that there was no significant difference among zones such as ticket lobby-concourse and concourse-platform.

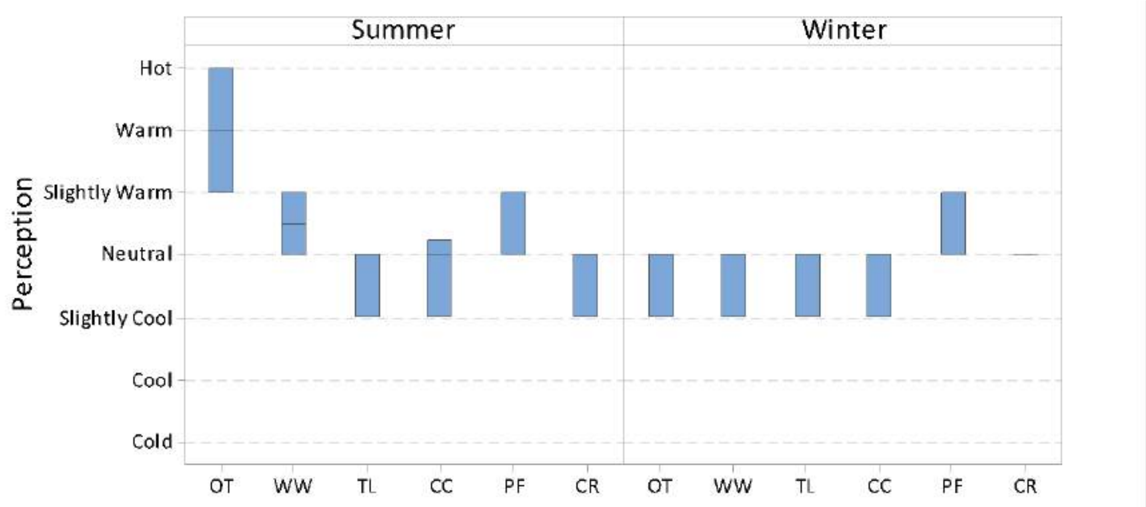


Figure 10 Passengers' perception at different location in both seasons

Figure 11 shows affective assessment of passengers at different zones in the metro stations. The results show 66% passengers reported comfortable thermal conditions during winter. However, during summer only 44% passengers reported comfortable thermal conditions. During the summer, 47.7% passenger preferred slightly cooler environment while in winter 60% of passengers preferred the environment without change. 92% of passenger found the environmental conditions in the metro station to be perfectly bearable in the winter while only 73% of passenger find station perfectly bearable in summer. During winter, 95% of passengers accepts the thermal environment without change. The platform was reported to be warm irrespective of season. More than 45% passengers wanted cooler thermal environment in the platform irrespective of seasons.

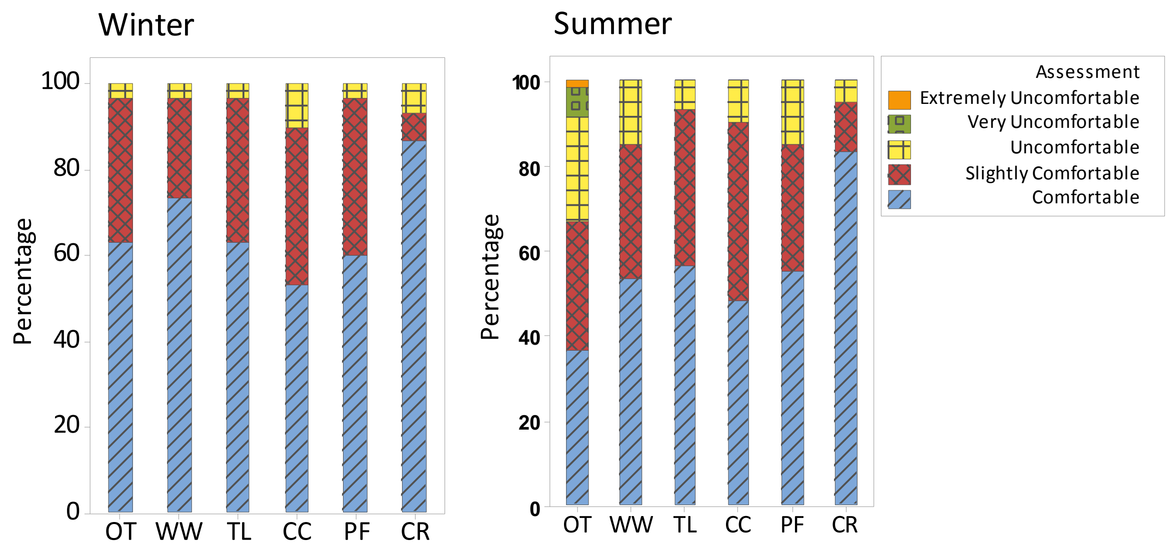
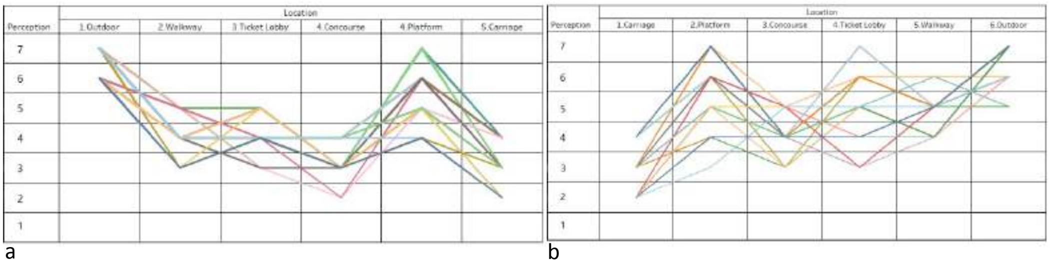


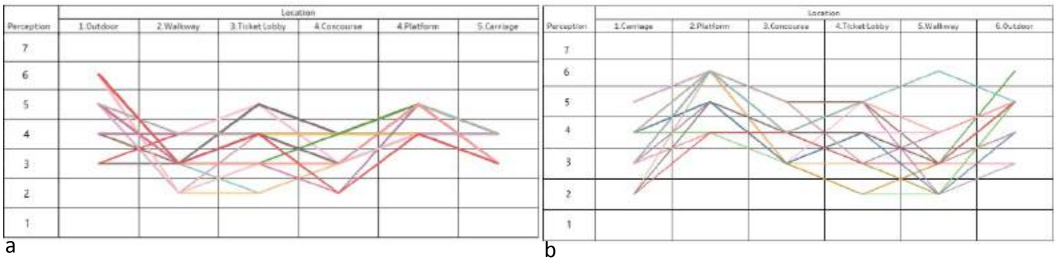
Figure 11 Passengers' affective assessment at different zones

Figure 12 and Figure 13 shows graph of the perception at various zones while performing respective sequence during summer and winter, each line represent sequence performed by the individual subject.



a b

Figure 12. Thermal perception during summer performing (a) boarding and (b) alighting



a b

Figure 13 Thermal perception during winter performing (a) boarding and (b) alighting

(1=Cold, 2=Cool, 3= Slightly Cool, 4=Neutral, 5=Slightly Warm, 6=Warm, 7= Hot)

Friedman test was conducted to analyse whether there is a significant difference in the thermal perception when passengers moves from one space to another space. Results shows that there is a significant difference ($p<.05$) in thermal perception when passengers perform boarding sequence. In order to check the significance of difference between consecutive zones while transitioning from one space to the other, Wilcoxon signed-rank test was conducted. The results show that there is no significant difference of thermal perception between Walkway and Ticket Lobby ($p>.01$). {Sig value=.05/5; Bonferroni adjustment} and ticket lobby and concourse. While performing alighting sequence there is no significant difference of thermal perception between concourse and walkway. However, there is a significant between carriage to platform and platform to concourse.

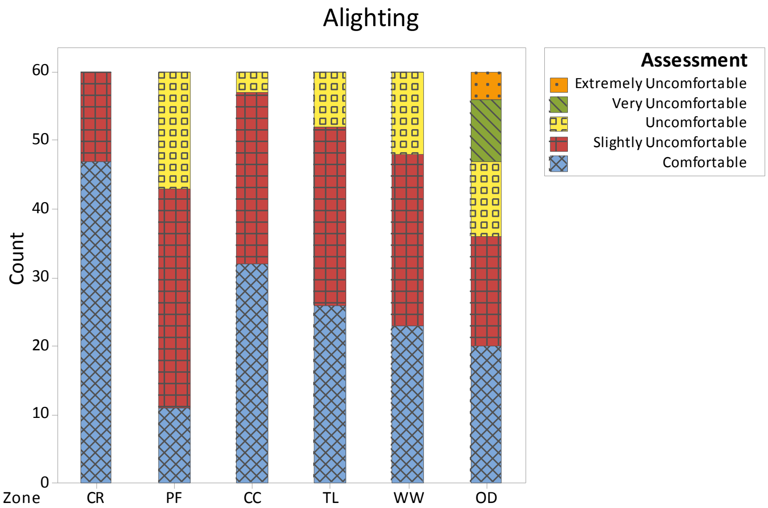


Figure 14 Affective Assessment during sequential survey performing alighting sequence

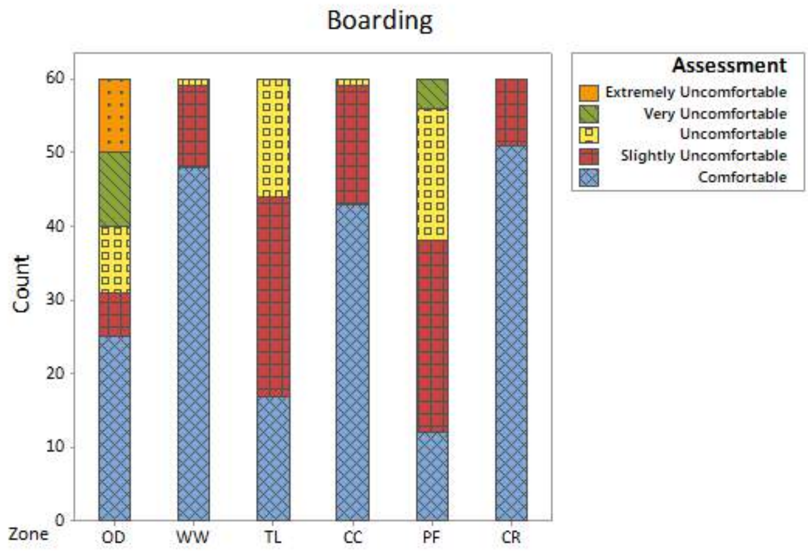


Figure 15 Affective Assessment during sequential survey performing boarding sequence

5. Discussion

5.1. Correlation between the thermal sensation vote and RWI

The regression analysis of thermal sensation vote collected using different survey methods corresponding to RWI at all the locations of the metro station is presented in Figure 16. The equation of the regression line for the TSV collected through sequential survey is

$$TSV_{sequential} = 4.44*RWI-1.02$$

The equation obtained using the thermal sensation collected through transverse survey is

$$TSV_{transverse} = 1.686*RWI-0.37$$

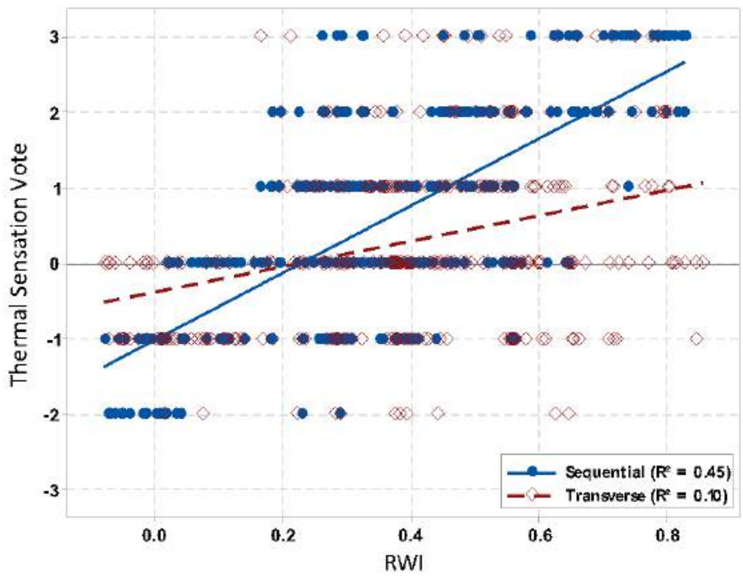


Figure 16 Correlation between the thermal sensation vote collected using different survey method and RWI

On comparing the regression coefficient of the above regression lines, it is observed that transverse survey could be good indicator of the acceptable limits of the RWI, but it is highly variables because of R^2 of only 0.10. While on other side, the sequential survey has coefficient of 0.45. This indicates that sequential survey could better assess the people perception in the transient application while transverse surveys are always good for steady state applications.

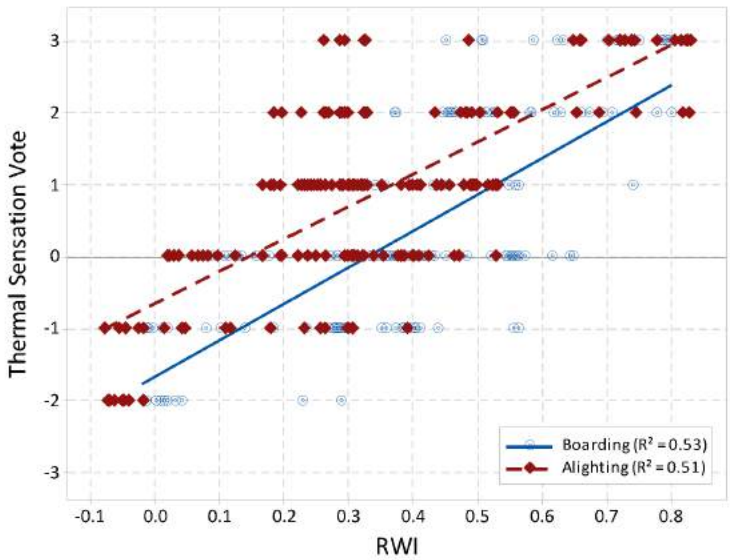


Figure 17 Correlation between the thermal sensation vote and RWI of both sequences

Figure 17 shows a correlation between Thermal sensation vote(TSV) and RWI calculated for boarding and alighting sequence. The regression analysis of TSV and RWI for different sequences is carried out. The regression equation of the boarding RWI is

$$TSV = 5.05*RWI_{boarding} -1.66$$

The equation for the regression for TSV and alighting RWI is

$$TSV = 4.5*RWI_{alighting} -0.64$$

There is a variation in the neutral RWI during the alighting and boarding sequence. The neutral value of RWI obtained through boarding sequence is 0.33 which is classified as hot as per ASHRAE classification. While neutral value of RWI for alighting sequence is 0.14 which is classified as warm.

5.2. Correlation between the thermal sensation vote and dry bulb temperature

The regression analysis of Thermal Sensation Vote (ASHRAE) and corresponding dry bulb temperature for all the identified zone in the metro station gives the neutral temperature for the whole metro ride. The equation of the regression line is

$$TSV=0.16TN -4.85$$

where, TSV=Thermal sensation vote,

TN=Neutral Temperature

It is observed that, thermal sensation scale (ASHRAE) seems to be a good indicator for thermal perception in the steady state conditions. It is highly variable in the case for a metro ride, since the R^2 value is only 0.42. The neutral temperature obtained using ASHRAE vote is 30.31°C.

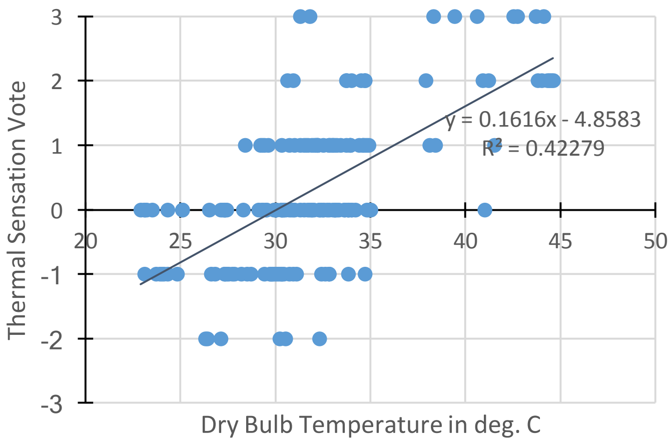


Figure 18 Correlation between the thermal sensation vote and dry bulb temperature

6. Conclusion

This paper presents the results of the thermal comfort assessment carried out in an underground metro station. Thermal comfort in terms of RWI varied

During the alighting sequence, mean RWI was found to be 0.36 which corresponds to Hot as per ASHRAE comfort classification. The mean RWI for boarding sequence was found to be 0.41 which also corresponds to Hot as per comfort classification. A comparative analysis of mean RWI indicates a gradual and uniform change along the alighting sequence of passenger flow. However, the variation of mean RWI is non-uniform and undulated along the boarding sequence. RWI varied from 0.26 at platform to 0.45 at the walkway along the alighting sequence. It varied from 0.3 at concourse to 0.51 at the ticket lobby along the boarding sequence. A statistically significant differences in thermal characteristics were found among the zones of the metro station. The platform observed highest temperature (33.6°C) among all the zones considered which is 2.2°C higher than the mean DBT of station. Subjective thermal assessment indicates a significant difference in thermal perception at different zones when passengers perform boarding sequence. However, there is no significant difference of thermal perception while passengers performed alighting sequence. Transverse survey could be a good indicator of the acceptable limits of the RWI, but it is highly variables (R^2=0.10). Sequential survey was found to be a better method to assess the subjective thermal perception. This is indicated by a better correlation (R^2= 0.45) with RWI as compared to transverse survey (R^2=0.10). A strong positive correlation was obtained between $TSV_{alighting}$ and RWI (R^2=0.51) as well as $TSV_{boarding}$ and RWI (R^2=0.53). An RWI value of 0.14 corresponded with mean neutral TSV for the alighting sequence while it was 0.33 for the boarding sequence. There is a variation in the neutral RWI during the alighting and boarding sequence. The neutral value of RWI obtained through boarding sequence is 0.33 which is classified as hot as per ASHRAE classification. While neutral value of RWI for alighting sequence is 0.14 which is classified as warm. The passengers exhibited higher level of tolerance to heat discomfort than that predicted by RWI. The neutral temperature obtained through thermal sensation vote collected at the identified zones is 30.3°C which is quite higher than referred studies.

7. References

Abbaspour, M. *et al.* (2008) 'Thermal comfort evaluation in Tehran metro using Relative Warmth Index', *International Journal of Environmental Science & Technology*, 5(3), pp. 297–304. doi: 10.1007/BF03326024.

Ampofo, F., Maidment, G. and Missenden, J. (2004a) 'Underground railway environment in the UK: Part 3: Methods of delivering cooling', *Applied Thermal Engineering*, 24(5–6), pp. 647–659. doi: 10.1016/j.applthermaleng.2003.10.019.

Ampofo, F., Maidment, G. and Missenden, J. (2004b) 'Underground railway environment in the UK Part 1: Review of thermal comfort', *Applied Thermal Engineering*, 24(5–6), pp. 611–631. doi: 10.1016/j.applthermaleng.2003.10.017.

Han, J., Kwon, S. bark and Chun, C. (2016) 'Indoor environment and passengers' comfort in subway stations in Seoul', *Building and Environment*. Elsevier Ltd, 104, pp. 221–231. doi: 10.1016/j.buildenv.2016.05.008.

Al horr, Y. *et al.* (2016) 'Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature', *International Journal of Sustainable Built Environment*. The Gulf Organisation for Research and Development, 5(1), pp. 1–11. doi: 10.1016/j.ijsbe.2016.03.006.

Katavoutas, G., Assimakopoulos, M. N. and Asimakopoulos, D. N. (2016) 'On the determination of the thermal comfort conditions of a metropolitan city underground railway', *Science of the Total Environment*. Elsevier B.V., 566–567, pp. 877–887. doi: 10.1016/j.scitotenv.2016.05.047.

Khalil, E. E. and El-Bialy, E. M. (2012) 'Experimental and computational investigation of flow regimes and thermal patterns in a subway station', *ASHRAE Transactions*, 118(PART 1), pp. 199–206. doi: 10.5923/j.ajfd.20120206.02.

Marzouk, M. and Abdelaty, A. (2014) 'Monitoring thermal comfort in subways using building information modeling', *Energy and Buildings*. Elsevier B.V., 84, pp. 252–257. doi: 10.1016/j.enbuild.2014.08.006.

Nakano, J. *et al.* (2005) 'Thermal Comfort Conditions in Train Stations for Transit and Short-Term Occupancy', *Department of Architecture, Tokai University, Japan*, pp. 1–8.

Ordódy, P. (2000) 'Thermal comfort in the passenger areas of the Budapest metro', *Periodica Polytechnica Mechanical Engineering*, 44(2), pp. 309–317.

Palma, G. A. V. and Stevenson, F. (2015) 'Thermal history and sequences in transitional spaces : Does order matter ?'

Patania, F. *et al.* (2012) 'Thermal comfort analysis of public transport passengers in Catania', *WIT Transactions on Ecology and the Environment*, 157, pp. 327–338. doi: 10.2495/AIR120291.

Subway Environmental Design Handbook V1. Second (1976). Washington DC: Subway Environmental Design Handbook.

Wang, Y., Feng, H. and Qi, X. (2013) 'SEED: Public Energy and Environment Dataset for Optimizing HVAC Operation in Subway Stations'.

Ye, X. *et al.* (2010) 'Investigation of indoor environmental quality in Shanghai metro stations, China', *Environmental Monitoring and Assessment*, 167(1–4), pp. 643–651. doi: 10.1007/s10661-009-1080-9.

Evaluation of Seasonal Thermal Environment of Temporary Shelters Built in Nepal after Massive Earthquake 2015

Rita Thapa[1], Hom Bahadur Rijal[2], Masanori Shukuya[3]

[1] Tokyo City University, Email: thapareeta19@gmail.com
[2] Tokyo City University, Email: rijal@tcu.ac.jp
[3] Tokyo City University, Email: shukuya@tcu.ac.jp

Abstract: Two major earthquakes struck in Nepal on 25th April and 12th May 2015. Especially, who lost their permanent house in this hardest hit has been living under makeshift tents. In Nepal, there is no such research has conducted yet based on different materials used as insulations in temporary shelters. Thus, this paper investigated to evaluate the seasonal indoor environment of temporary shelters where using various local materials used as insulations. Thermal measurements were conducted for 26 days in winter for seven shelters (S1-S7) and 24 days in summer for three shelters (S1-S3) located in Lalitpur district. The indoor air temperatures for all shelters are highly dependent on outdoor air temperature in winter and summer. The fluctuations of indoor air temperature of shelter S3 and S7 is higher than other shelters in both seasons. The result might be due to low thermal insulations in these shelters. The mean indoor air temperature during the sleeping time is 5.4°C in S7 and 10.1°C in S1 in winter. The mean indoor air temperatures are considerably low in winter and high in summer where people are compromising these harsh indoor environments by adapting their clothing behaviours.

Keywords: Nepal-Earthquake, Temporary shelter, Thermal environment, Thermal insulation, Thermal adjustment

1. Introduction

Two major earthquakes struck Nepal in 25th April and 12th May 2015, affected around 6 million people, across many districts of the country (Dhital et al. 2016). Two years after the devastating earthquake, nearly 71% of the affected people still living in temporary shelters built of zinc or tarpaulin sheet (Varughese et al. 2016). After this earthquake zinc, plastic or tarpaulins sheets were handed to the people who lost their houses for the purpose of making temporary shelters where roof and the walls were made of zinc sheet. Temporary shelters are vital part of humanitarian relief and play a fundamental role for the initial stages of disasters. People try to build makeshift shelters themselves by using their traditional method and available materials. Most of the people were not aware of how the indoor environment could be improved, in spite of the fact that they are using various materials used as insulations to mitigate that harsh environment. However, these thermally very conductive materials, which could not protect from unwanted heat gains and lose the heat from summer and winter. Temporary indoor environment inside the makeshift shelters can hardly provide the people with fully sufficient conditions but minimum conditions in order to protect from heavy rain, scorching sun, wind and bitter coldness.

Several studies have been carried out to related thermal evaluation of indoor temperature through roof and wall temperature (Shinohara et al. 2014, Ponni & Baskar 2014). Some researches focused on the design and construction in the post-disaster temporary housing during the emergency phase (Abulnour 2014, Arslan & Cosgun 2008, Cassidy 2007) and some researchers have focused on simulation to improve of temporary shelters (Obyn et al. 2015, Salvalai et al. 2015, Ying et al. 2016). In the context of Nepal, some researches have been done to relate the thermal environment and thermal comfort of temporary shelters (Thapa & Rijal 2016, Thapa et al. 2018) and evaluate the indoor air temperatures on the basis of different materials used as insulations applying to temporary shelters (Thapa et al. 2017).

This research paper tries to evaluate the indoor thermal environment in winter and summer where people are adapting their thermal environment by taking different behaviours according to the change of seasons. For such purpose in mind this paper reports the measured indoor thermal environment of those shelters built in Nepal on the basis of different materials used as insulations in different season.

2. Methodology

2.1. Investigated areas and description of shelters

The investigations were conducted in seven different thermally insulated temporary shelters located in Lalitpur district as shown in Figs. 1 & 2. These all investigated temporary shelters are made of zinc sheet but insulated methods and materials are different from each other. In winter, we have focused on two shelters S1 and S7, and in summer, same shelter of S1 and other S3 in particular, comparison between them, one has better insulating and other thermally poorest.

During the investigated time we found shelter S1 had applying good thermal insulation to protect from outdoor environment and high heat capacity of thermal insulation comparison to shelter S7 and S3. Table 1 shows the detail of insulated materials for the investigated temporary shelters. Those living in temporary shelters tried to mitigate their problems and reduce thermal discomfort of temporary shelters by using their own ideas and techniques. For example, people used local and available materials such as plastics/ tarpaulins, black/white foam, straw mat and plywood under or over the zinc sheet for winter and summer as shown in Fig. 3. These thermal insulations are applying for the temporary shelters, which helps to reducing unwanted heat losses or heat gains.

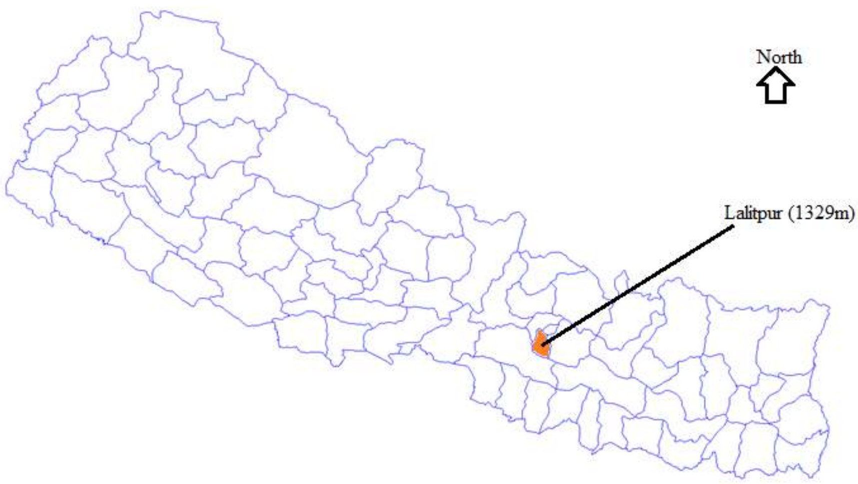


Fig. 1 Map of Nepal with investigated district (The number in the bracket denote the altitude)

(a) S1

(b) S2

(c) S3

(d) S4

(e) S5

(f) S6

(g) S7

Fig. 2 Investigated temporary shelters (S1-S7 for winter and S1-S3 for summer)

(a) Straw and dry grasses on the roof

(b) Black or white foam under the celling

(c) Plastic sheet under the celling, straw mat and papers paste on wall

Fig. 3 Examples of applied local materials used as insulations, (a) outdoor insulations (straw), and (b and c) indoor insulations (black foam and tarpaulin)

Table 1 Description of investigated shelters

Shelter Code	No. of people	Place	Length (mm)	Width (mm)	Height (mm)	Wall	Roof	Pillar	Window	Shading	Door	Floor	Roof Insulations
S1	4	Bishnudol	5000	3470	2100	Up to 600 mm mud and brick wall, upper side zinc sheet	Rectangular	Wood	3 open iron, East, West & south facing	Thin curtain, Plastic	Wood, South facing	Brick, Mud and Carpet	Outdoor straw, indoor clothes and black or
S2	9	Bishnudol	9200	2100	2100	Up to 300 mm mud and brick wall, upper side zinc sheet	Rectangular	Bamboo	None	None	Zinc, North facing	Mud and Carpet	Outdoor straw, indoor thin clothes and
S3	3	Lubhoo	2550	1800	1800	Zinc sheet	Dome	Iron	None	None	Wood, North facing	Mud and cover by Carpet	Indoor black foam
S4	4	Imadol	6800	3100	2800	Zinc sheet	Rectangular	Iron	Open glass, East & West facing	Thick curtain	Zinc, North facing	Plaster and thick Carpet	Indoor thick clothes
S5	2	Imadol	6300	3400	2800	Zinc sheet	Rectangular	Iron	Open glass, North & South facing	Thick curtain	Zinc, West facing	Plaster and thick Carpet	Indoor thick clothes
S6	3	Jyagata	3450	2600	2150	Bamboo and mud plaster	Rectangular	Wood, bambo	Open wood, North facing	Thin curtain	Zinc, West facing	Mud and Mattress	Indoor clothes and black foam
S7	4	Lubhoo	9000	3900	2700	Up to 700 mm front and other three side 300 mm brick and cement wall and upper side	Rectangular	Iron	2 Fixed glass, 1 open glass West facing	Thin curtain, Plastic	2 door Zinc , West facing	Mud and Mattress	Indoor thin clothes

2.2. Thermal measurement in winter and summer

The measurements were conducted for 26 days (January 20th to February 14th, 2016) in winter and 24 days (March 29th to April 21st, 2016) in summer as shown Fig. 4. Environmental parameters such as indoor air temperature (T_i), indoor globe temperature (T_g), Indoor relative humidity (RH_i) and outdoor air temperature (T_o) were measured by data logger at the interval of 10 minutes. We have measured outdoor air temperature just outside the shelter S1 and we assumed the same outdoor air temperature for the rest of shelters because all seven shelters were within the range between 50 m to 6 km.

Fig. 4 Installed instruments in temporary shelters

3. Thermal environment in winter

3.1. Variations of indoor and outdoor air temperatures

Fig. 5 shows the 24 hours indoor and outdoor temperature profile for a typical one day (1st February, 2016) of seven shelters. We have selected that day because there was no drastic deviation in weather condition. The indoor air temperatures are close to outdoor air temperatures for all shelters. The indoor air temperature of shelter S7 is sharply increasing (maximum 23°C) and decreasing (minimum 3°C) during the day and night time. Indoor air temperature of S7 also seems lower to outdoor air temperature during the night time. The results indicate that indoor air temperature of shelter S7 was approximately 6°C lower than outdoor air temperature at night time compare to shelter S1. The result might be due to low thermal insulations are used in shelter S7 (Table 1). So, it can be said that the thermal insulation is one of the most effective measures to improve the indoor air temperature. According to Ponni & Baskar (2014), roof and walls are important element which directly receives the solar radiation in different angle than other elements of the building and it receives the heat or cold and also responsible to the outside thermal variations. As for other shelters, the indoor and outdoor air temperatures are gradually increase and decrease. But case of shelter S3 indoor air temperature is sharply increasing about 27°C and decreasing about 7°C during the day time. The result might be the poorest insulations among other six shelters and also least heat storing capacity.

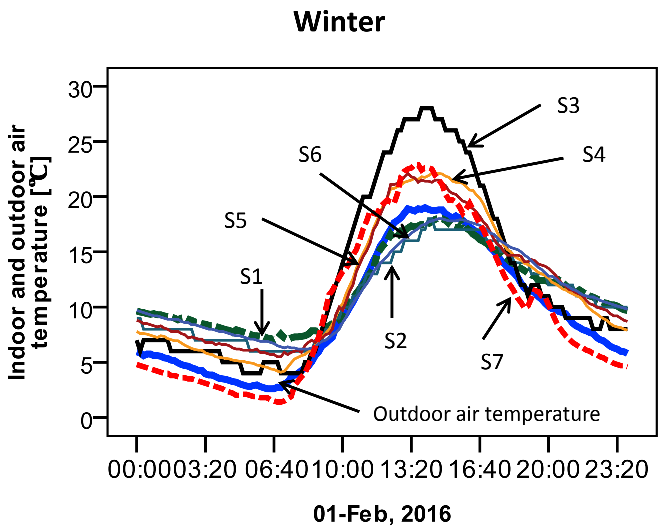


Fig. 5 Variation of indoor and outdoor air temperature in a day in winter

3.2. Mean indoor temperature during sleeping time

Table 2 shows the result of mean indoor and outdoor temperature of day time, night time and sleeping time in winter. Here, in this section we focused to analyse the mean indoor air temperature for sleeping time. The mean indoor air temperature during the sleeping time has found large difference (4.7°C) between S1 (10.1°C) and S3 (5.4°C) in winter. The mean maximum indoor air temperature of ordinary building is 12 to 15°C (Bajracharya 2013), which is higher than temporary shelters. It seems that the overall mean indoor air temperature is very low and respondents are compromising the indoor environment by adapting their clothing insulations. The mean clothing value was found 1.29 clo in winter (Thapa et al. 2018).

Table 2 Mean indoor air temperature and standard deviation in winter

S.C	Variables	Day time (6:00-17:50)			Night time (18:00-5:50)			Sleeping time (21:00-5:50)		
		N	Mean	S.D	N	Mean	S.D	N	Mean	S.D
S1		1800	13.0	3.9	557	12.6	2.0	1297	10.1	1.7
S2		1800	12.4	4.2	557	11.9	2.6	1297	9.5	2.1
S3		1800	16.7	8.0	557	11.8	2.7	1297	8.2	2.5
S4	T_i	1224	15.6	6.4	306	14.0	1.5	918	8.3	2.1
S5		1224	15.2	5.7	306	14.2	1.4	918	9.0	1.9
S6		1224	13.5	4.5	306	14.3	1.4	918	9.9	1.8
S7		1224	14.8	6.9	306	11.4	2.0	918	5.4	2.3
All Shelters	T_o	1800	12.0	5.7	557	10.0	2.9	1297	5.7	2.3

S.C: Shelter code, S: Shelter, N: Number, S.D.: Standard Deviation [°C], T_i: Indoor air temperature [°C] , T_o: Outdoor air temperature [°C]

4. Thermal environment in summer

4.1. Variations of indoor and outdoor air temperatures

Fig. 6 shows the variations of indoor and outdoor temperature for a typical one day (10th April, 2016) of three shelters. We have selected that day because there was clear weather condition. The indoor air temperature difference of S1 and S2 are smaller (2 to 3°C). But, the indoor air temperature in S3 fluctuates most; the maximum reaches about 38°C in day time and minimum reaches 13°C in night. The highest indoor air temperature at 38°C in S3 is approximately 6°C higher than outdoor air temperature. This result might be due to no ventilation and thermally poorest materials used as insulations. As mention in Table 1 and Fig. 3, these thermally conductive materials used as insulation are not sturdy enough to protect from harsh climatic conditions during summer. The people compromise such a high temperature by adapting clothing behaviours where we found the mean clothing value of 0.52 clo in summer (Thapa et al. 2018).

Hence, these investigated shelters were made of zinc sheet which directly receives the solar radiation in different angle, and also responsible to the outside thermal variations. If the thermal mass of walls and roof is less then the transmission of heat is more during the day time.

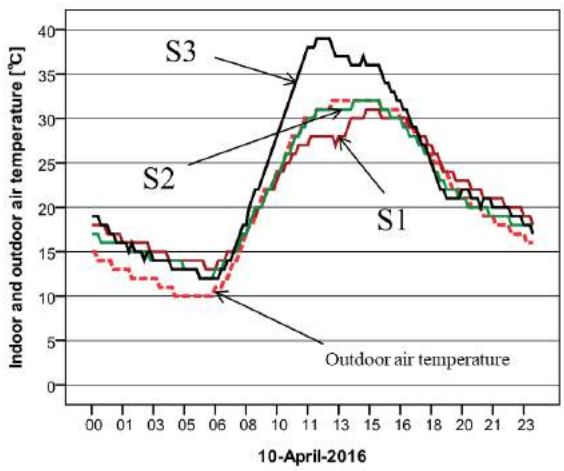


Fig. 6 Variation of indoor and outdoor air temperature in a day in summer

4.2. Relationship between indoor and outdoor air temperature

Fig. 7 shows the relationship between indoor and outdoor air temperature of three shelters for all 24 days. The indoor air temperatures for all shelters are highly dependent on outdoor air temperature. These results suggest that where there is no ventilation, the indoor air temperature tend to be higher than outdoor air temperature. To improve the indoor environment in summer, it is necessary to bring fresh outdoor air at lower temperature by natural ventilation. Here, we have obtained the following regression equation of three shelters to predict the indoor air temperature by outdoor air temperature.

S1 $T_i = 0.760T_o+5.9$ (N= 3368, R^2=0.937, S.E.= 0.003, p<0.001) (1)

S2 $T_i = 0.861T_o+3.8$ (N= 3368, R^2=0.979, S.E.= 0.002, p<0.001) (2)

S3 $T_i = 1.096\ T_o+0.48$ (N= 3368, R^2=0.893, S.E.= 0.007, p<0.001) (3)

N: number of sample, R^2: coefficient of determination, S.E.: standard error of the regression coefficient, p: significance level of the regression coefficient.

The slope of equation (1), 0.760 is slightly lower than equations (2) and (3). It suggests that S1 indoor air temperature is better than other two shelters in summer.

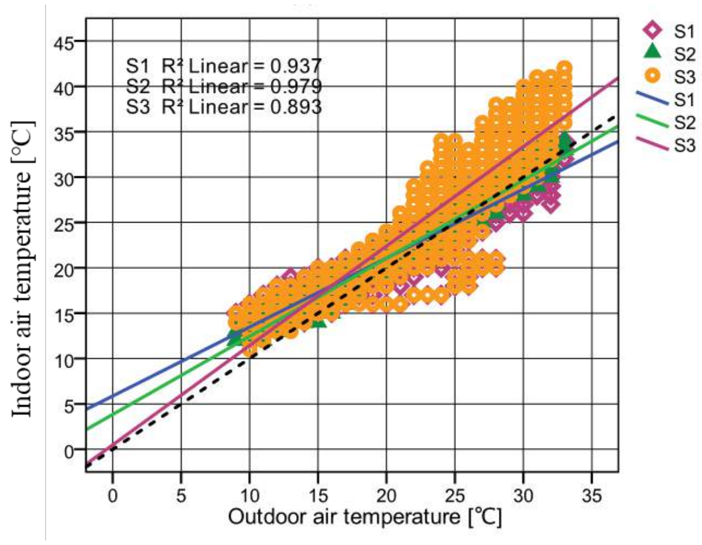


Fig. 7 Relationship between indoor and outdoor air temperature of three shelters in summer

4.3 Mean temperature of day, night and sleeping time

Table 3 shows the result of mean indoor and outdoor temperature of day, night and sleeping time of three shelters in summer. The mean day time temperature of S1 is 27.1°C which is 4.1°C lower than S3. The mean indoor air temperature of S3 range between 17.2 and 31.2°C which are close to previous research of traditional houses (17.8 to 32.0°C) in Nepal (Rijal et al. 2010), and in temporary shelters (25 to 30°C) built after Wenchuan earthquake in China (Huang et al. 2015). The mean night time indoor air temperature is almost similar to each other in all shelters.

Table 3 Mean temperature and standard deviation in summer

S.C	Variables	Day time (6:00-17:50)			Night time (18:00-5:50)			Sleeping time (21:00-5:50)		
		N	Mean	S.D	N	Mean	S.D	N	Mean	S.D
S1		828	27.1	3.3	864	17.3	1.8	1278	17.3	1.8
S2	T_i	828	28.1	3.3	864	16.9	1.9	1278	16.9	1.9
S3		828	31.2	5.3	864	17.2	2.1	1278	17.2	2.1
All Shelters	T_o	828	28.0	3.3	864	14.7	2.3	1278	14.7	2.3

S.C: Shelter code, S: Shelter, N: Number, S.D.: Standard Deviation [°C], T_i: Indoor air temperature [°C] , T_o: Outdoor air temperature [°C]

5. Conclusions

In this paper, we have measured the indoor thermal of temporary shelters in winter and summer. The results are found as follows.

1. The indoor air temperatures for all shelters are highly dependent on outdoor air temperature in winter and summer.
2. Shelter S1 has good thermal insulations are applying for mitigate their thermal discomfort in both seasons comparison to other shelters.
3. The fluctuations of indoor air temperature of shelter S3 and S7 are higher than other shelters in winter.

4. The mean indoor air temperature during the sleeping time has found large difference (4.7°C) between S1 (10.1°C) and S3 (5.4°C) in winter.
5. The fluctuation of mean indoor air temperature of S3 is higher than S1 during the summer.
6. The mean indoor air temperature during the sleeping time is almost similar for all shelters in summer.

Acknowledgements

We would like to give thanks to Hikaru Imagawa for his assistance to data analysis and Arun Khatri K.C. for helping in the field measurement

References

Abulnour A.H., 2014. The post-disaster temporary dwelling, Fundamental of provision, design and construction. Housing and Building National Research Center, HBRC Journal. vol. 10, pp. 10-24.

Arslan H., Cosgun N., 2008. Reuse and recycle potentials of the temporary house after occupancy: Example of Duzce, turkey. Building and Environment. vol. 43, pp.702-709.

Bajracharya S.B., 2013. Investigation of thermal environment of the traditional houses of Kathmandu valley. AIJ conference, Kanto, Research Meeting, pp. 141-144.

Cassidy J., 2007. Strategic planning for post-disaster temporary housing. Article in Disasters. vol. 3I (4), 435-458.

Dhital M.R., Rijal M.L., Bajracharya S.R., 2016. Landslide dams and their hazard after the 25th April 2015 Gorkha Earthquake in Central Nepal. Lowland Technology International: Special Issue on; Nepal Earthquake & Disaster, vol. 18, (2), pp. 129-140.

Huang L., Long E., Ouyang J., 2015. Measurement of the thermal environment in temporary settlements with high building density after 2008 Wenchuan earthquake in China. Procedia Engineering. vol. 121, (95), pp. 95-100.

Shinohara N., Tokumura M., Kazama M., Yonemoto Y., Hasegawa K., Yoshino H., Yanagi U., 2014. Indoor air quality and thermal comfort in temporary houses occupied after the Great East Japan Earthquake. vol. 24, pp. 425-437.

Obyn S., Moeseke van G., Virgo V., 2015. Thermal performance of shelter modelling: Improvement of temporary structures. Energy and Buildings. vol. 89, pp. 170-182.

Ponni M., Baskar R., 2014. Evaluation of indoor temperature through roof and wall temperatures- An experimental study in hot and humid climate, International journal of engineering and innovative technology, vol.4, (6), pp. 205-211.

Rijal H.B., Yoshida H., Umemiya N., 2010. Seasonal and regional differences in neutral temperatures in Nepalese traditional vernacular houses. Building and Environment. vol.45, (12), pp. 2743-2753.

Salvalai G., Imperadori M., Scaccabarozzi D., Pusceddu C., 2015. Thermal performance measurement and application of a multilayer insulator for emergency architecture. Applied Thermal Engineering. vol. 82, pp. 110-119.

Thapa R. & Rijal H.B., 2016. Study on thermal environment and thermal comfort in autumn season of temporary shelters in Nepal after massive earthquake 2015, Lowland Technology International, vol. 18 (2), pp. 119-128.

Thapa R., Rijal H.B., Shukuya M., 2018. Field study on Acceptable Indoor temperature in temporary shelters built in Nepal after massive earthquake 2015. Building and Environment. Accepted for publication, 3rd March, 2018.

Thapa R., Rijal H.B., Shukuya M., 2017. Comparison of wintery indoor air temperature in temporary shelters built in Nepal after massive earthquake 2015. Architecture Institute of Japn (AIJ), Summaries of Technical Papers of Annual Meeting, Hirosima. pp. 515-516.

Thapa R., Rijal H.B., Shukuya M., 2017. Evaluation of Summer Thermal environment of temporary shelters built in Nepal after massive earthquake 2015. Architecture Institute of Japn (AIJ), Kanto. pp. 13-14.

Varughese G., Barron P., 2016. Aid and recovery in Post-Earthquake Nepal. Independent Impacts and Recovery Monitoring, Phase 3. Quantitative Survey. The Asia Foundation.

Ying Y., Enshen L., Yuan S., Hongxing Y., 2016. Assessing the thermal performance of temporary shelters. Procedia Engineering. vol. 159, 174-178.

Thermal environment ranges providing good sleep quality in bedrooms during summer – Analysis of university students in Osaka

Noriko Umemiya[1], Hirona Bessho[1], Tomohiro Kobayashi[1], Yoshiki Tachibana[1] and Yusuke Nakayama[1]

[1]Graduate School of Engineering, Osaka City University, umemiya@arch.eng.osaka-cu.ac.jp

Abstract: A questionnaire survey and bedroom thermal environment measurements were conducted for 24 university students for 581 nights in the peak of summer for three years to clarify subjective ranges of thermal comfort and good sleep quality. Results revealed the following. 1) Thermal comfort decreased as the standard effective temperature (SET*) increased when SET* was more than 21°C. 2) The SET* range at which more than 80% voted in three central categories of seven-point thermal sensation scale was 19.3–22.7°C, 'thermally acceptable' temperatures were 17.7–28.0°C. The good side of the sound sleep evaluation scale was 20.1–23.7°C. 3) Subjective sleep quality decreased gradually when SET* exceeded 22°C. However, sleep quality related to Drowsiness and Fatigue recovery increased when SET* exceeded 26°C. 5) The ratio of 'thermal comfort' for air conditioner※AC) non-use nights peaked when SET* was 20°C, although it peaked at 25°C for AC use nights. 6) Subjective sleep quality decreased as SET* increased for AC non-use nights, although it peaked at 25°C for AC use nights.

Keywords: Sleep Quality, Thermally Comfort Range, Air Conditioner use

1. Introduction

In 2010, outdoor temperatures in Osaka remained higher than 25°C for 55 nights. Sultry nights have been increasing because of global warming. People are adversely affected by the heat: sleep quality decreases especially in urban areas with heat island phenomena. Lower sleep quality affects daytime work performance and causes financial loss. Sometimes, it affects health. More than 1700 people died from heat stroke in 2010 in Japan. More than half died in their homes. Governments implore people to use air conditioners (AC) appropriately to avoid heat stroke, but governments also call for AC temperature setting of 28°C in campaigns to protect the environment: COOLBIZ. For most people and governments, concrete methods of thermal control use remain unknown.

A survey taken by Sakane et al. (2012) of more than 300 Osaka apartment house residents revealed that 54.4% and 29.0 % of people who possessed 2–3 air conditioners did not use AC, respectively, in daytime and nighttime. More than 60% responded that they chose not to use AC partly because of high electric bills and partly because of reasons unrelated to cooling. Electrical power shortages related to the severe accident at the Fukushima Daiichi nuclear power plant caused by the Tohoku earthquake in 2011 possibly influenced their decisions related to AC use.

Given such circumstances, this study was conducted to clarify the range of thermal comfort, thermal acceptability, and good sleep quality during peak summer using thermal environment measurements and a subjective evaluation survey of university students. 1) Is there any difference among thermal sensation, thermal comfort, and acceptability during summer sleep? 2) What are the thermal comfort and good sleep quality ranges of thermal environments? 3) How do the ranges differ between nights of AC use and AC non-use?

2. Methods

2.1. Measurement procedure

Surveys of 83 students were conducted for 581 days over three years. The students, who lived in or near Osaka, participated in a survey of seven successive days in summer. They measured bedside temperatures at 10 min intervals. Relative humidity was recorded before and after sleep. Every morning, they filled in questionnaire sheets about the prior night, reporting sleep quality on 15 four-point-scales, thermal sensation on a seven-point-scale, thermal comfort on a four-point-scale, and thermal acceptability on a three-point-scale in bedrooms. They also maintained a diary recording their absence or presence in bedrooms, personal AC use, electric fan use, window opening of the bedrooms, and sleeping or awakening at 30 min intervals.

2.2. Method of Sleep quality evaluation

Subjective sleep quality was evaluated using the OSA sleep quality inventory. The OSA sleep evaluation method was developed by Oguri, Shirakawa and Azumi in 1985 based on nearly seven hundred subjects. The OSA score is an average of five factors of a T-score calculated from subjective rating scales of sleep quality for. Sleep quality was evaluated by 16 four-point-scales: very good, somewhat good, somewhat bad, or very bad. 16 scales were classified into five factors. Higher scores indicate higher sleep quality.

The five factors were the following: Factor I (Drowsiness when waking such as 'I have the power of concentration.', 'I feel a sense of liberation.', and 'I feel clear-headed.'), Factor II (Falling asleep and maintaining sleep such as 'I was able to sleep soundly.', 'I dozed off until I finally fell asleep.', 'I got to sleep easily.', 'I often woke up from sleep.', and 'The sleep was shallow.'), Factor III (Dreaming, such as 'I had many nightmares.' and 'I had many dreams.'), Factor IV (Fatigue recovery such as 'Fatigue persists after waking up.', 'I feel languorous.', and 'I feel unwell.'), and Factor V (Sleeping duration such as 'I have generally good appetite.' and 'The sleep duration was long.').

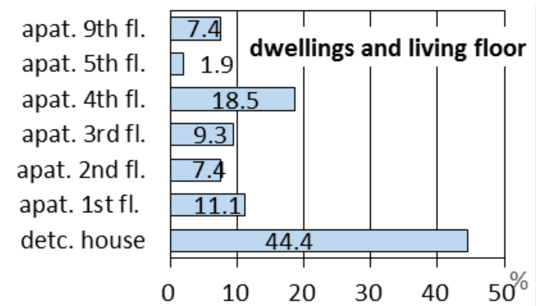
2.3. Attributes of the subjects

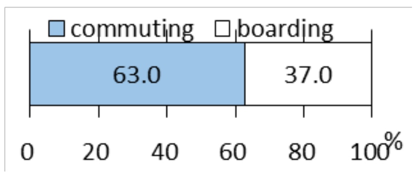
Fig. 1 presents the frequency distribution of basic attributes of the subjects. 37.0% were boarding. 54.1% answered that they could bear summer heat only by natural ventilation. 36.2% had slightly bad circulation. 63.8% had slightly irregular sleep habits.

3. Results

3.1. Thermal environment

Fig. 2 presents the frequency distribution of standard effective temperature (SET*), which was averaged during sleeping. Here, air velocity was assumed as 0.2 m/s when AC or natural ventilation as used and was assumed as 0.2 to 2.5 m/s according to the intensity of electric fans. Clothing insulation was inferred from a subject's survey responses. The metabolic rate was inferred as 0.9 met. The global temperature was presumed as equal to the air temperature. SET* was 19°C – 31°C, but 26°C was the most frequent. The mean was 25.7°C.





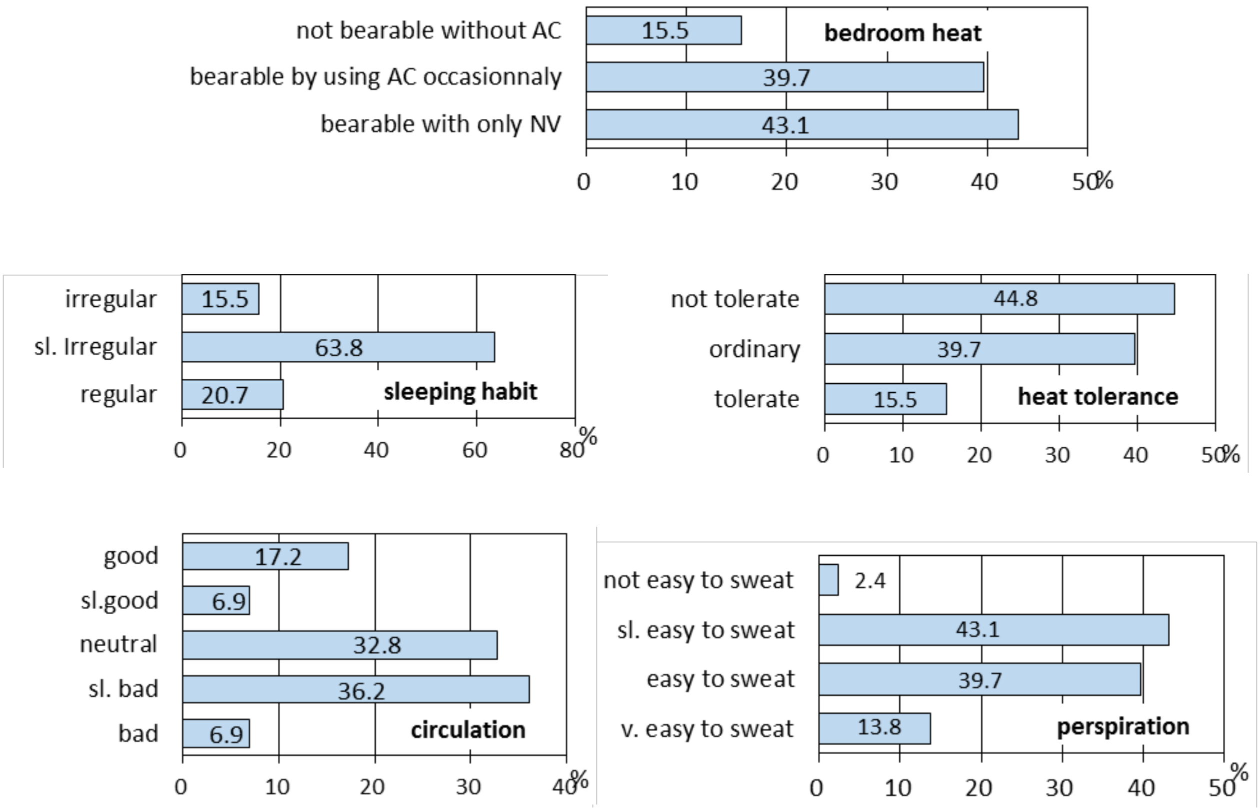


Fig.1 Frequency distribution of living environment and subjects attributes

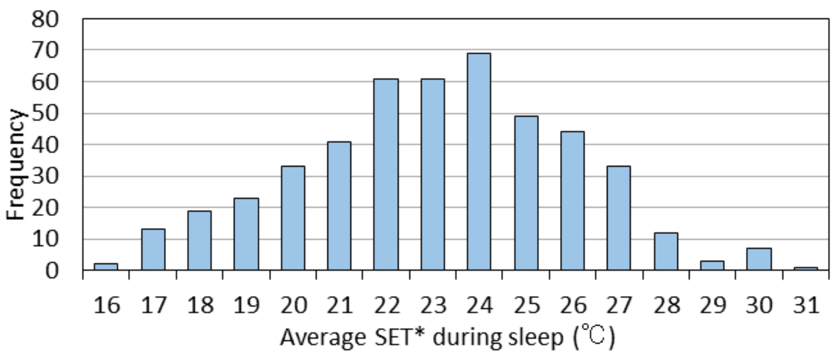


Fig.2 Frequency distribution of average SET* during sleep

3.2. Subjective evaluation

3.2.1. Thermal sensation

Fig. 3 presents a frequency distribution of thermal sensation and clothing. Results show 'neutral' as the most frequent (34.8%) thermal sensation, 'comfort' was most frequent (62.6%) in thermal comfort, and 'acceptable' was most frequent (85.8%) in acceptability. Then 'slightly warm' (26.0%), 'slightly uncomfortable' (30.8%) and 'sometimes unacceptable' (12.9%) were next.

'Half sleeve shirts and half pants' were the most frequent clothing ensemble (68.9%). 'Half sleeve shirts and long pants' were next (10.0%).

3.2.2. Subjective sleep quality evaluation

Fig. 4 portrays frequency distributions of the degree of sound sleep and OSA score. Each OSA score represents the mean of seven nights. ‘Slightly good’ was the most frequent response (61.3%). The most frequent OSA score was 50.0. The average OSA score was 48.3. The standard deviation was 2.9.

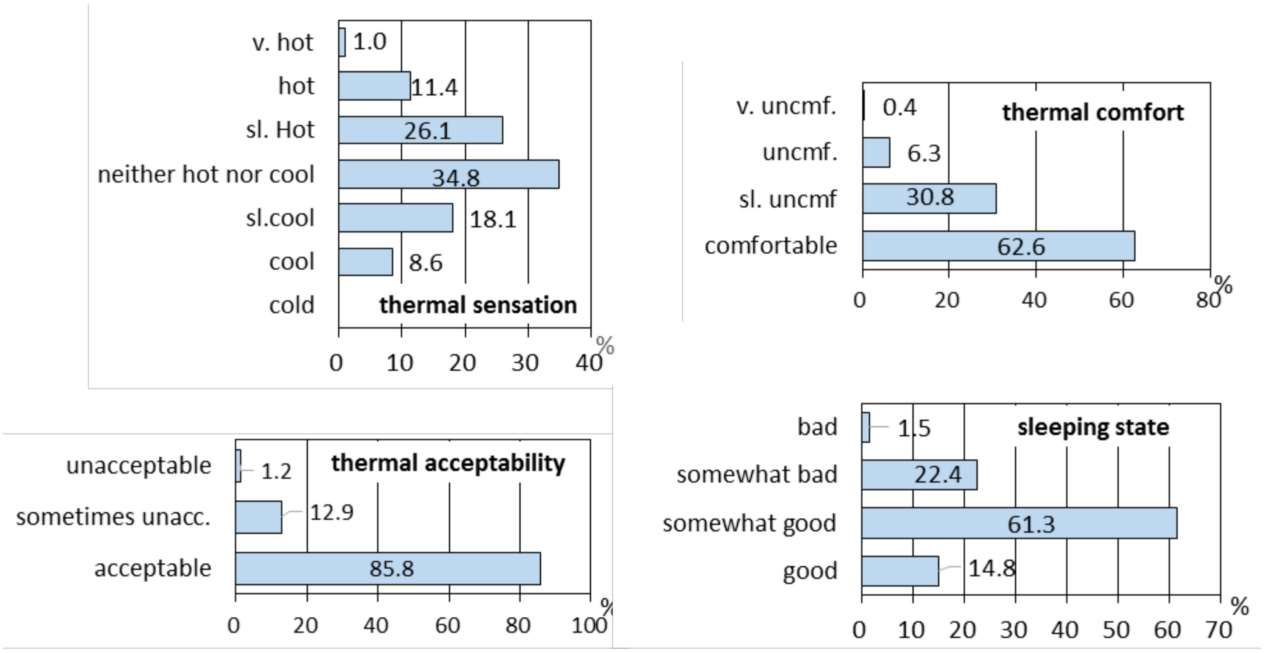


Fig.3 Frequency distribution of thermal sensation and sleep state

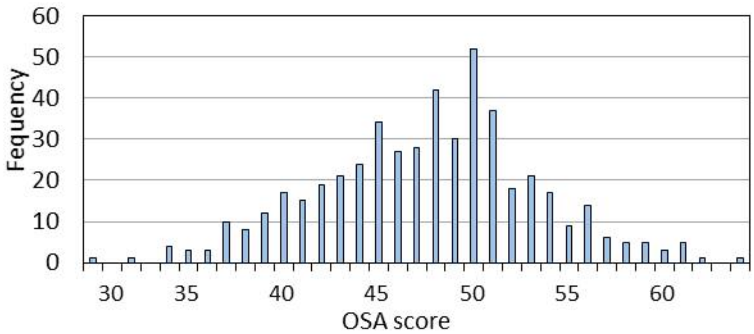


Fig.4 Frequency distribution of OSA score

4. Comfort ranges

Fig. 5 portrays the comfort ratios for each mean SET* during sleep. Five comfort ratios were defined as ratios of 1) ‘neutral’ on the seven-point thermal sensation scale, 2) central three categories in the seven-point thermal sensation scale, 3) ‘comfort’ in the four-point thermal comfort scale, 4) ‘acceptable’ in the three-point thermal acceptability scale, and 5) ‘good’ and ‘slightly good’ in the four-point sound sleep scale. Comfort ratios decreased as SET* increased when SET* was more than 21°C, especially for the ratio based on thermal neutrality and the ratio based on thermal comfort.

Fig. 6 displays the SET* range, where the comfort ratio exceeds 80%. The comfort ranges were 19.3°C – 22.7°C, 17.7°C – 28.0°C, and 20.1°C – 23.7°C, respectively, based on the central three categories of thermal sensation, thermal acceptability, and the good side of sound sleep evaluation.

Fig. 7 presents a scatter plot of the thermal environment of 'good' and 'slightly good' sleep compared with ASHRAE thermal comfort range. The operable temperature for good sleep

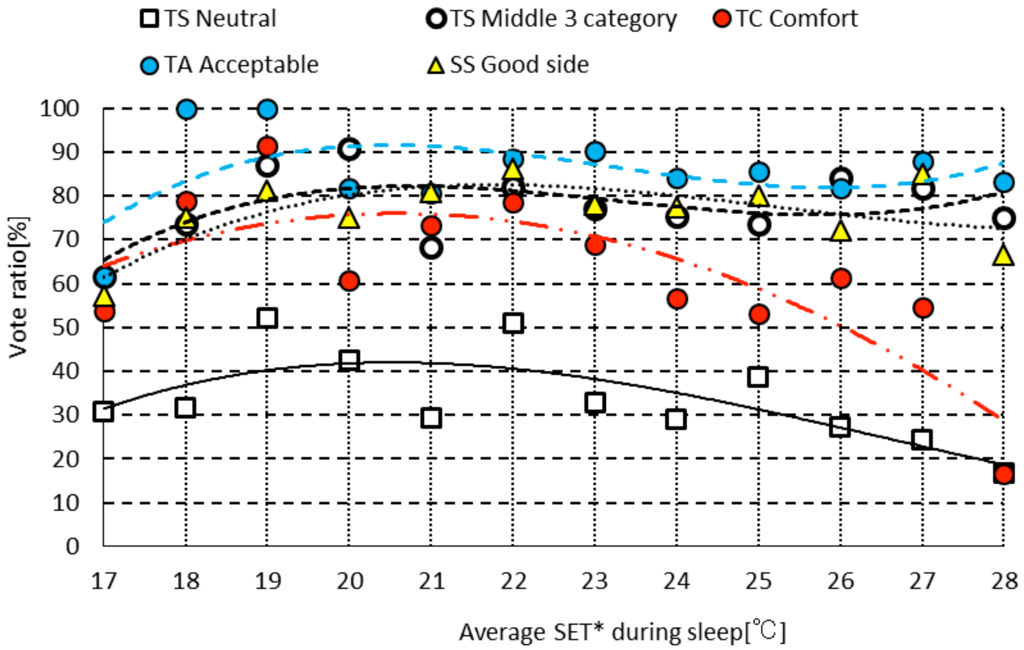


Fig.5 Voting ratio of thermal sensation and sleep state for each average SET* during sleep

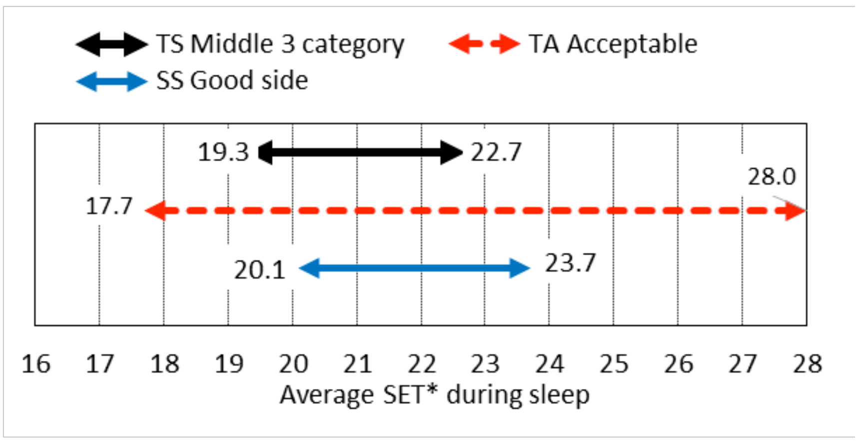


Fig.6 'Comfort' ranges of thermal sensation, acceptability and sleep state

was 22.0°C – 24.9°C, which was warmer than the ASHRAE summer comfort zone. Thermal insulation of bed clothes were not considered in calculations of these SET*. Therefore, the comfort thermal environment might be warmer.

Fig. 8 displays another comfort ratio based on the OSA score. Here the comfort range was defined as a 75 percentile OSA score value that was 51.2 for Total OSA, 50.0 for Factor I (Drowsiness), 52.2 for Factor II (Falling asleep and maintaining sleep), and 51.1 for Factor IV (Fatigue recovery). The Total OSA score decreased gradually when SET* exceeded 22°C, although it was independent of SET* when SET* was lower than 22°C. The OSA scores of Drowsiness and Fatigue recovery were higher irrespective of SET*, but they decreased when

SET* exceeded 21°C and increased when SET* exceeded 26°C. This tendency was stronger for Fatigue recovery. The OSA score of maintaining sleep tended to increase slightly as SET* increased.

The comfort ratio based on the total OSA score tended to decrease as SET* increased, but tendencies differed for different OSA factors.

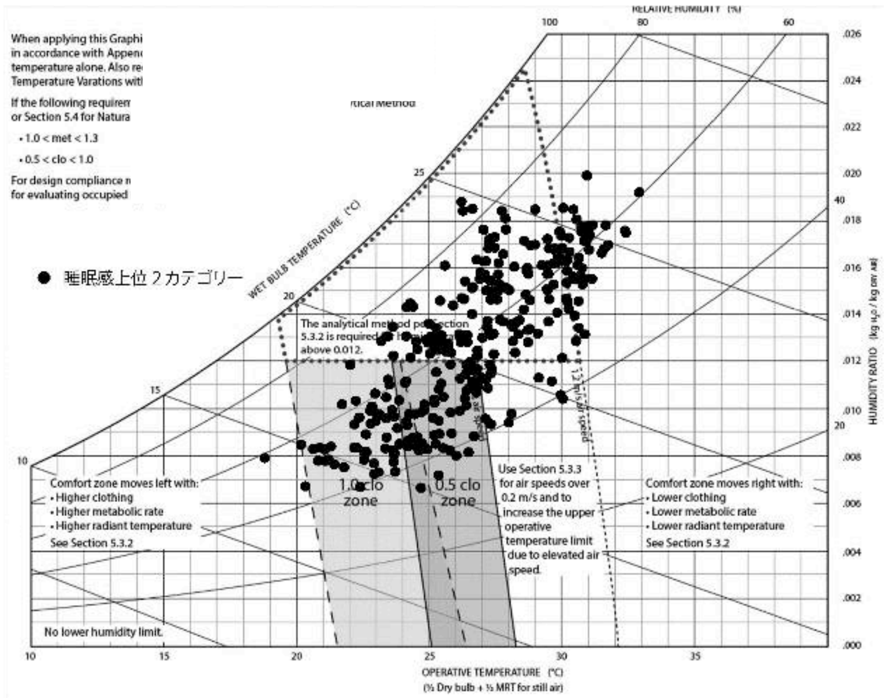


Fig.7 Scatter plot of 'good' side sleep state evaluation on ASHRAE comfort zone

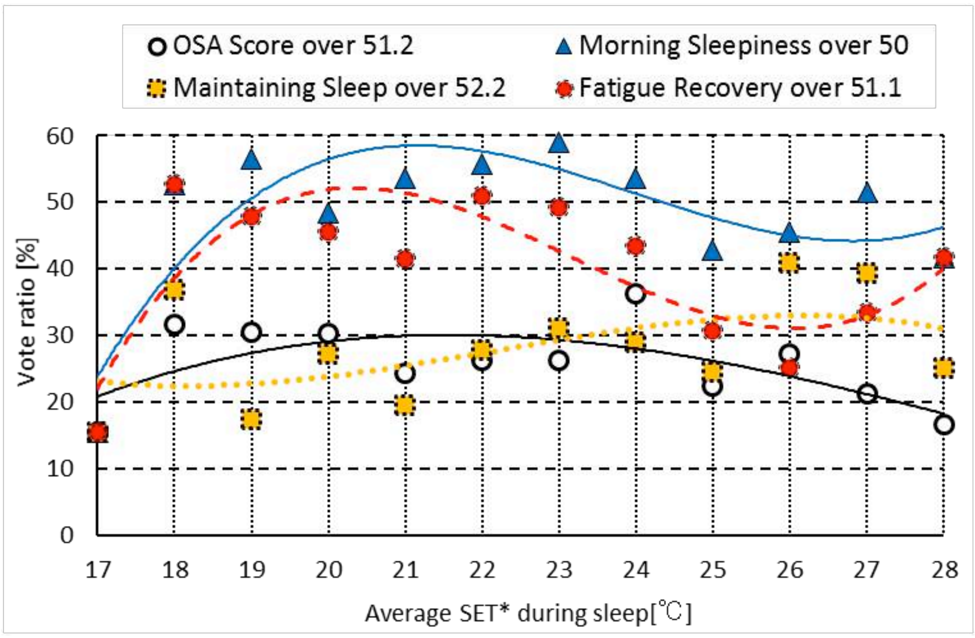


Fig.8 Ratio of high OSA score (>75 percentile value) for each average SET* during sleep

5. Comparison between AC use and AC non-use nights

Fig. 9 presents a comparison of comfort ratios based on thermal sensations between AC use nights and AC non-use nights.

The comfort ratio based on 'neutral' in thermal sensation was higher on AC use nights than on AC non-use nights when SET* was 23°C – 25°C, although a reverse tendency was observed when SET* was 22°C or 26°C. It can be said that in a temperate thermal environment, the ratio of 'neutral' votes was higher for AC use nights, but in rather edge temperatures, the ratio of 'neutral' votes was higher for AC non-use nights. The comfort ratio based on three central categories of thermal sensation votes exhibited a similar tendency: it was higher on AC non-use nights than on AC use nights when SET* was 22°C. The comfort ratio based on thermal acceptability scores was also higher on AC non-use nights than on AC use nights when SET* was 22°C. The comfort ratio based on the thermal comfort score was higher on AC use nights than on AC non-use nights for all SET* bins, but ratios were almost equal for AC use nights and AC non-use nights when SET* was 22°C or 26°C. It can be said that comfort ratios for AC non-use nights peaked when SET* was 20°C. They peaked when SET* was 25°C for AC use nights.

Fig. 10 presents a comparison of comfort ratios based on OSA scores for AC use nights and AC non-use nights. The ratio of high OSA score decreased as SET* increased for AC non-use nights in all OSA, OSA of Factors I (Drowsiness), II (Maintaining), and IV (Fatigue recovery). However, for AC use nights, the ratios of high OSA were higher at 25°C than at other SET* values.

6. Conclusions

Zones of high sleep quality and thermal comfort in summer were investigated using measurements of thermal environments in bedrooms and subjective evaluations for 24 bedrooms for 581 nights. Data for AC use nights and AC non-use nights were compared.

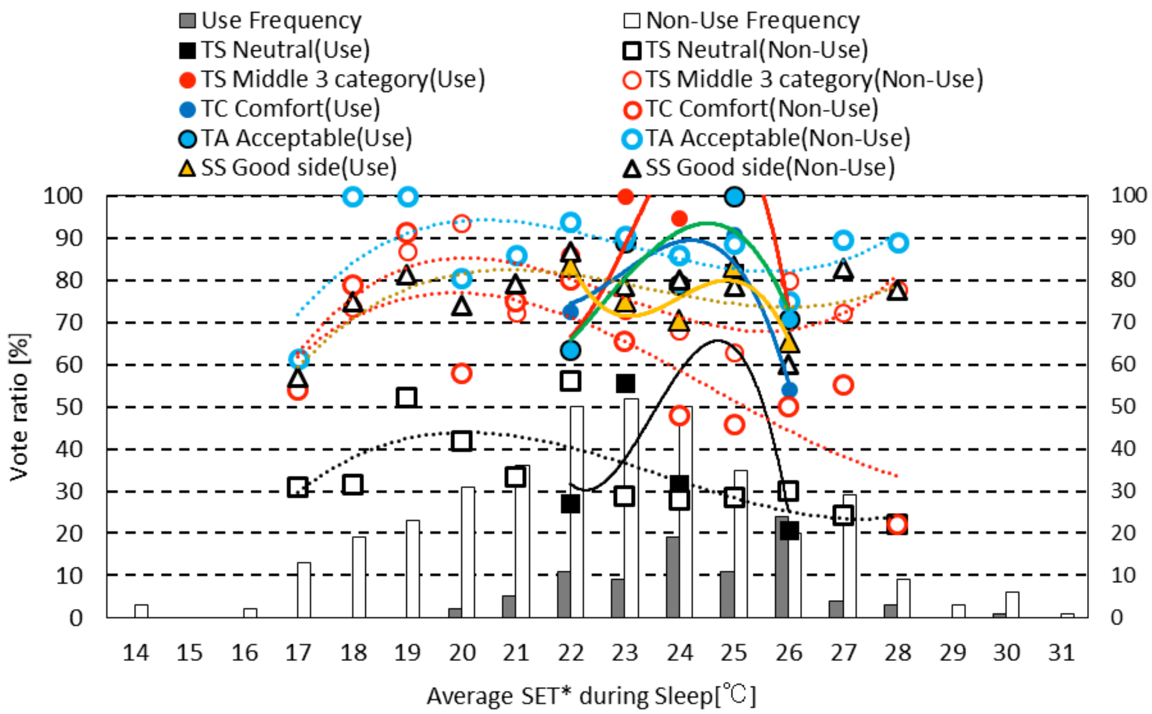


Fig.9 Voting ratio of thermal sensation and sleep state for each average SET* during AC use and non-use nights

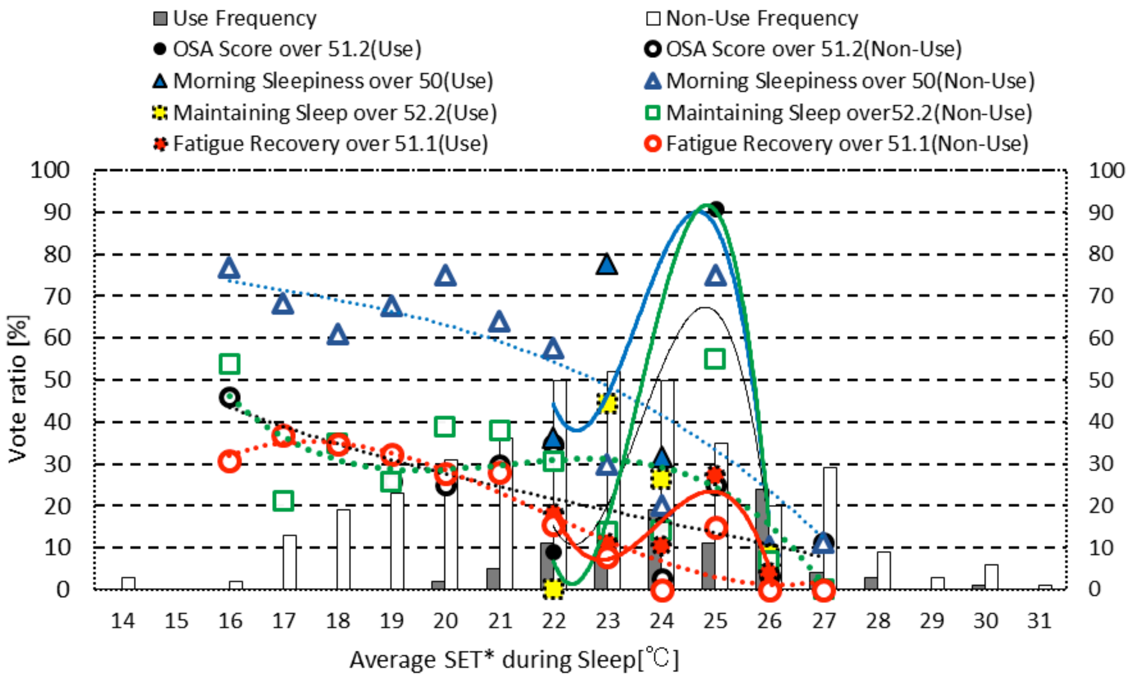


Fig.10 Ratio of high OSA score (>75 percentile value) for each average SET* during AC use and non-use nights

1) Comfort ratios decreased as SET* increased when SET* was higher than 21°C, especially for the ratio based on thermal neutrality and the ratio based on thermal comfort.
2) The SET* range at which more than 80% voted in three central categories of seven point thermal sensation scale was 19.3–22.7°C. 'Thermally acceptable' was 17.7–28.0°C. The good side of sound sleep evaluation scale was 20.1-23.7°C.
3) Operable temperatures for the good sleep side of sound sleep evaluation scale were 22.0°C – 24.9°C, which was warmer than the ASHRAE summer comfort zone.
4) Subjective sleep quality decreased gradually when SET* exceeded 22°C. Sleep quality related to Drowsiness and Fatigue recovery increased when SET* exceeded 26°C, especially for Fatigue recovery.
5) The ratio of 'thermally comfortable' for AC non-use nights peaked when SET* was 20°C, although it peaked at 25°C for AC use nights.
6) Subjective sleep quality decreased as SET* increased for AC non-use nights, although it peaked at 25°C for AC use nights.

7. References

Japan Meteorological Agency, 2016. Latest weather, http://www.data.jma.go.jp

Oguri. M et al., 1985. Development of OSA sleep quality inventory – Statistical construction and standardization of rating scale for evaluation of subjective sleep sensation. *Clinical Psychiatry*, 27(7), pp 791-798.

Sakane. T et al., 2013. Relation among sleep, thermal comfort and thermal control use during summer in 2012. *Proceedings of annual meeting of Kinki branch of the Society of Heating, Air-Conditioning Sanitary Engineers of Japan*, vol.42, pp 173-176.

Umemiya. N et al., 2016. Air-Conditioner Use Effects on Thermal Environment and Sleep Quality in Bedrooms during Summer -Analysis of University Students in Osaka, Proceedings of 9th Windsor Conference, 7-4.

Yamamoto. Y et al., 1999. Standardization of revised version of OSA sleep inventory for middle age and aged. *Brain Science and Mental Disorders*, 10(4), pp 401-409.

Proceedings of 10th Windsor Conference
Rethinking Comfort

Windsor Conference 2018 www.windsorconference.com

Organised by

ECHI LTD

Supported by

nceub
Network for Comfort and Energy Use in Buildings

HERIOT WATT UNIVERSITY

LONDON METROPOLITAN UNIVERSITY
THE CASS

Sponsored by

VELUX®

Published by NCEUB 2018 www.nceub.org.uk

ISBN 978-0-99289 57-8-5

9 780992 895785 >