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Impact of Residents' Past Thermal Experiences on Thermal Comfort and Energy Performance in a High-Rise Residential Building

by

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ABSTRACT

FACULTY OF ENGINEERING & THE ENVIRONMENT

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IMPACT OF RESIDENTS' PAST THERMAL EXPERIENCES ON THERMAL COMFORT AND ENERGY PERFORMANCE IN A HIGH-RISE RESIDENTIAL BUILDING

by Rucha Amin

Domestic space heating accounts for 19% of the UK's total energy demand. Studies have shown that occupants' behaviours and preferences can have a significant influence on space heating use. Currently the energy performance models used to estimate energy use assume occupants to be a homogeneous group with similar thermal preferences. However, studies conducted in numerous locations across the world have found that peoples' preferences for their indoor environment are closely linked to the local climate. This work investigated the influence of moving from one climate to another on thermal preferences in a residential setting and the associated energy implications.

The study employed field studies conducted over three consecutive academic years, including one pilot study, in a University halls of residence in Southampton, UK. The first full field study (n=47) consisted of four rounds of face-to-face survey visits conducted in occupants' accommodation rooms with in-situ environmental measurements and long term indoor air temperature monitoring. The second full field study (n=22) collected survey responses using a custom-built smartphone app with long term indoor air temperature monitoring. The findings from these studies informed a dynamic simulation energy model that was used to investigate the impact of diversity in set point temperature, occupancy pattern and ventilation strategy on overall space heating demand.

Key findings from this work indicated that there are statistically significant differences in temperature preference between long term and new UK residents. This is also reflected in the actual indoor temperatures maintained by occupants. Furthermore, there was no evidence found that these preferences change over the first six months of occupancy. The results also highlighted the importance of indoor thermal history, in addition to outdoor climate, in determining people's expectations for the indoor environment. From these findings, a conceptual model for understanding adaptive thermal comfort in conditioned spaces was formulated and explored. Energy performance modelling revealed substantial differences in space heating demand based on diversity in occupants preferences and behaviour. This is likely to have implications for building managers in cases where occupants are from mixed climatic backgrounds.

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Declaration of Authorship

I, Rucha Amin, declare that this thesis entitled *Impact of Residents' Past Thermal Experiences on Thermal Comfort and Energy Performance in a High-Rise Residential Building* and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University;
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- Where I have consulted the published work of others, this is always clearly attributed;
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

Parts of this work have been published as:

- Amin, R., Teli, D., James, PA., Bourikas, L., 2016, The influence of students' 'home' climate on room temperature and indoor environmental controls use in a modern halls of residence, Energy and Buildings, 119, pp.331-339. DOI: 10.1016/j.enbuild.2016.03.028
- Amin, R., Teli, D., James, PA., Exploring the link between thermal experience and adaptation to a new climate, *International Journal of Future Cities & Environment (In Review)*
- Conference papers: Amin et al. (2015), Amin et al. (2016), Amin et al. (2017)

Signed:

Date:

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Glossary of terms

AC	Air conditioned
ACH	Air changes per hour
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
C_{int}	Internal CO_2 concentration
C_{ext}	External CO_2 concentration
CIBSE	Chartered Institute of Building Service Engineers
clo	Clothing insulation
DR	Draught rate
DSY	Design summer year
EPC	Energy performance certificate
HDD	Heating degree days
ISO	International Organization for Standardization
met	Metabolic rate
NV	Naturally ventilated
PMV	Predicted Mean Vote
POE	Post occupancy evaluation
PPD	Percentage Predicted Dissatisfied
RH	Relative humidity
SCATs	Smart Controls and Thermal Comfort
T_a	Air temperature
T_{com}	Comfort temperature
T_g	Globe temperature
T_{op}	Operative temperature
TRNSYS	Transient system simulation tool
TRY	Test reference year
TSV	Thermal Sensation Vote
U-value	Thermal transmittance of materials

Chapter 1

Introduction

Energy efficiency measures are being addressed in a number of sectors with a view to manage carbon emissions and avoid worsening climate change impacts. The UK emissions reduction target aims to reduce carbon emissions to 80% of 1990 levels by 2050 (Climate Change Act 2008). Domestic space heating alone accounts for 19% of the UK's total energy demand (BEIS 2017). While the technology to build highly efficient, low energy homes already exists, the challenge for designers is to provide functional and comfortable dwellings whilst maintaining low energy use. Given the UK climate, much of the challenge of engineering comfort lies in providing a satisfactory indoor thermal environment. Presently, occupants are assumed to be a homogenous population with similar indoor thermal preferences based on studies carried out in temperate climates.

However, it is clear from studies conducted in different climates that indoor comfort temperatures vary based on local climate (de Dear & Brager 1998). This principle forms the basis of the theory of adaptive thermal comfort. Fundamentally, adaptive thermal comfort theory asserts that thermal preferences are determined by a combination of physiological, psychological and behavioural mechanisms (de Dear & Brager 1998). Whilst the impact of these mechanisms on thermal preference in a single location has been studied extensively, the effect of moving from one climate to another is not well understood. In June 2017, immigration to the UK totalled 572,000 with 141,000 people arriving for formal study and 261,000 for work (ONS 2017). This implies that considering the indoor environmental parameters with respect to occupants of mixed climate histories is of significance to designers and policy makers alike.

Few studies have been conducted globally to investigate this particular question and many of those that have were conducted in climate chambers where participants' personal preferences or behaviours are not accounted for (Yu et al. 2013; Chun et al. 2008; Kalmár 2016; Luo, Ji, et al. 2016). Of the few field studies that have been conducted, only a handful have been conducted in residential buildings (Ning et al. 2016; Fuller & Bulkeley 2013) where occupants are free to manage their environments to suit their preferences. This work aims to address this knowledge gap by exploring diversity in occupants' preferences and its link to thermal history in a residential setting.

1.1 Research Aims & Objectives

1.1.1 Aims

This work investigates if there are significant differences in comfort temperature between occupants who have moved to the same residential complex from different climates. The research also aims to understand if comfort temperatures change over time when residents move from one climate to another given the option to create their preferred environment. This work also explores a new conceptual model for understanding thermal comfort in a new setting. Additionally, the energy performance implications of occupants from mixed climate backgrounds are considered. The investigation is carried out using a modern, 1100 room case study building; the University of Southampton's Mayflower Halls of Residence complex.

1.1.2 Objectives

- To identify indoor environmental patterns of occupants with difference climate experiences using long term monitoring data of temperature and humidity.
- To investigate seasonal variation in comfort temperatures relative to a 'home' climate.
- To explore differences in behaviour with respect to personal experience and previously experienced climate using additional information from participants regarding general temperature perception and use of indoor environmental controls.
- To explore a conceptual model for predicting thermal comfort in a new climate
- To investigate the impact of diversity in occupants' indoor thermal history on energy use using a dynamic simulation energy model.
- To explore and assess management strategies for the case study building to optimise residents' thermal comfort.

1.2 Publications

This section summarises the formal outputs from this work. These include a journal paper published in Energy & Buildings, a journal paper in review at the International Journal of Future

Cities & Environment, three peer reviewed conference papers presented at SET 2015, Windsor 2016 & SET 2017 and a Post Occupancy Evaluation report.

1.2.1 Journal papers

Amin, R., Teli, D., James, PA., Bourikas, L., 2016, The influence of students' 'home' climate on room temperature and indoor environmental controls use in a modern halls of residence, *Energy and Buildings*, 119, pp.331-339. DOI: 10.1016/j.enbuild.2016.03.028

The focus of this paper is understanding differences in reported use of indoor environmental controls and indoor temperature preference based on occupants' primary location of residence for the two years prior to moving to Mayflower Halls. The key finding from this paper was that residents from climates classified as 'warm/hot' based on winter temperature compared to the UK maintained an indoor room temperature approximately 2°C higher than those from 'cool/cold' climates representing ~20% increase in the annual heating demand of a dwelling in the UK. This paper is based on the analysis conducted for the paper presented at 14th International Conference on Sustainable Energy Technologies (see above). The major development from the conference paper is to show that this observed 2°C difference indoor temperature cannot be explained by room orientation alone. The full paper can be found in Appendix A-I.

Relevant chapters: Literature Review (2), Study Design (3.2, 3.3), Results & Discussion (4.1, 4.2, 4.3, 4.4)

Amin, R., Teli, D., James, PA., Exploring the link between thermal experience and adaptation to a new climate, *International Journal of Future Cities & Environment (In Review)*

This paper presents findings from a 6 month field study which consisted of long term temperature monitoring and a series of four face-to-face thermal comfort surveys. Results found significantly higher indoor temperatures in rooms occupied by residents from other cold and other hot climates. This is likely to be due to familiarity with heating systems and embedded heater use behaviour. Similarly, there were significant differences found in the comfort temperature between groups in some surveys. The relationship between indoor air temperature and comfort temperature was found to be strongest in the long term UK residents which supports the adaptive principles. The full paper can be found in Appendix A-II.

Relevant chapters: Literature Review (2), Study Design (3.2, 3.4), Results & Discussion (5.2)

1.2.2 Conference papers

Amin, R., Teli, D., James, PA., Bourikas, L., 2015, Harnessing Post Occupancy Evaluation to understand student use of indoor environmental controls in a modern halls of residence, *Proceedings of the 14th International Conference on Sustainable Energy Technologies (SET),* Nottingham, UK.

This paper formed the basis of the Energy & Buildings journal paper described in Section 1.2.1.

Relevant chapters: Literature Review (2), Study Design (3.2, 3.3), Results & Discussion (4.1, 4.2, 4.3, 4.4)

Amin, R., Teli, D., James, PA., 2016, Investigating the impact of thermal history on indoor environmental preferences in a modern halls of residence complex, *Proceedings of 9th Windsor Conference: Making Comfort Relevant,* Windsor, UK.

The results of this paper show a range of comfort temperatures of over 10°C across the three month study period. The first survey (October) found no significant difference between residents when grouped by previous climate of residence. The second survey (December) found that the mean comfort temperature for residents from the UK had dropped by 1°C, despite an unseasonably warm winter, and mean comfort temperatures for residents from other climates remained the same. This could be an indication of psychological adaptation whereby residents accustomed to the UK climate expect cooler temperatures moving from October to December and thus come to prefer this. The full paper can be found in Appendix A-III.

Relevant chapters: Literature Review (2), Study Design (3.2 3.4), Results & Discussion (5.1, 5.2.1, 5.2.2)

Amin, R., Teli, D., James, PA., Exploring the link between thermal experience and adaptation to a new climate, *Proceedings of the 16th International Conference on Sustainable Energy Technologies (SET)*, Bologna, Italy.

This paper formed the basis of the Future Cities & Environment journal paper described in Section 1.2.1.

Relevant chapters: Literature Review (2), Study Design (3.2, 3.4), Results & Discussion (5.2)

1.2.3 Technical reports

Bourikas, L., Teli, D., Amin, R., James, PA., Bahaj, A., 2015, Post Occupancy Evaluation report: Mayflower Halls of Residence

This industry focussed Post Occupancy Evaluation report has been produced to provide feedback to the designers and building management team. The study found that the building performed very well with regards to electricity, water usage and heat demand with accommodation rooms remaining well above the design minimum temperature of 19°C.

However, questionnaire and interview responses indicate that there may be some issues with ventilation and high temperature during warmer periods. Also included in the report are suggestions for improvement; the POE summary report can be found in Appendix A-IV.

1.3 Thesis structure

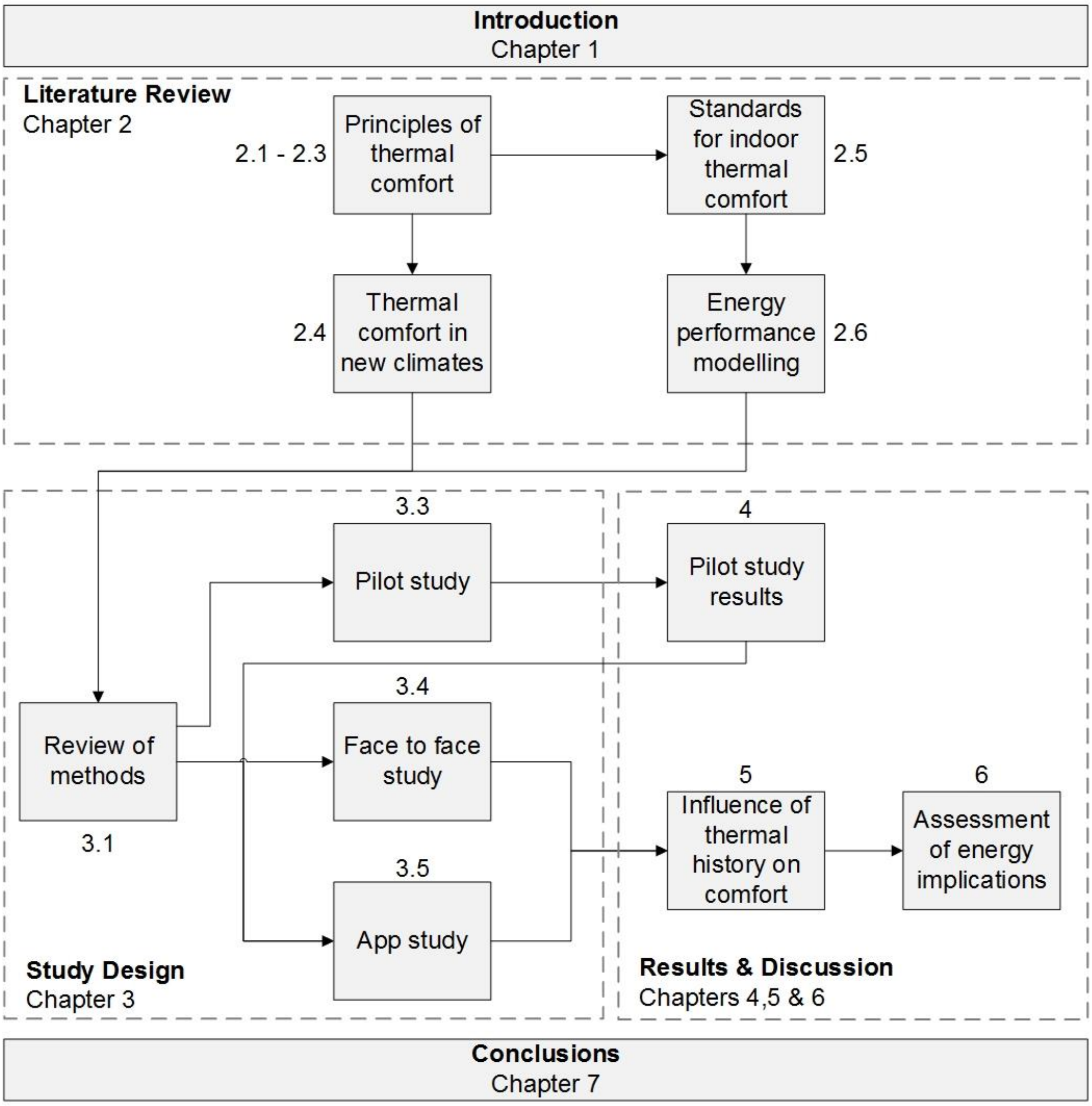


Figure 1.1 Thesis structure

Chapter 2

Literature Review

This section presents a review of the principles of human thermal comfort in indoor environments including current approaches and studies addressing understanding diversity in comfort conditions. Also covered are existing standards for indoor thermal comfort which provide a framework for designers and finally, a review of building energy performance assessment.

2.1.1 Indoor thermal comfort

Thermal comfort is defined as (ASHRAE 2013):

The state of mind which expresses satisfaction with the thermal environment

It is widely understood that no indoor climate is able to satisfy everyone due to biological, physiological and preferential differences but rather, the aim of understanding thermal comfort is to be able to provide an indoor environment which satisfies the greatest number of people. Based on the definition above it is possible for the body to be in heat balance (i.e. the thermoregulatory system has maintained the core body temperature) and still experience dissatisfaction with the environment. An example of this situation given by Nicol et al. (2012) is a person with a warm head and cold feet. In general, human thermal comfort in the indoor environment is said to be determined by six major factors: radiant temperature, air temperature, air velocity, relative humidity, clothing insulation and activity level (Nicol et al. 2012; Fanger 1970). Models of thermal comfort can be grouped into two main categories: 'rational' or 'heat balance' approaches and 'empirical' or 'adaptive' approaches. The first, heat balance approaches, are based primarily on physics and physiology and aim to understand comfort with respect to heat flow in and out of the body using climate chambers studies. Adaptive approaches, on the other hand, are likely to employ field studies where participants are based in their usual environment for example in an office or residential setting.

2.2 Heat balance approach to thermal comfort

A pioneering heat balance approach to thermal comfort was set out by Fanger in the 1970s and is known as the Predicted Mean Vote (PMV) model. Fanger's work was based on the idea that since the six factors responsible for thermal comfort (radiant temperature, air temperature, air velocity, relative humidity, clothing insulation and activity level) are not independent of each other and thus their effect must be considered collectively (Fanger 1970). This forms the basis of Fanger's general comfort equation which combines a heat balance equation for the human body with values for mean skin temperature and sweat secretion. The use of mean skin temperature and sweat secretion as conditions for thermal comfort is based on climate chamber experiments in which University aged students were asked to carry out some standard activities while dressed in particular clothing under different thermal conditions; at the same time, skin temperature and sweat secretion of the participants was measured.

A heat balance is said to exist in the human body when exposed to a constant, moderate thermal environment since heat production will equal heat dissipation (Fanger 1970). This balance is regulated by the thermoregulatory system which is responsible for all process which serve to maintain this balance such as shivering and sweating. The equation governing this relationship is as follows:

$$H - E_d - E_{SW} - E_{re} - L = K = R + C$$

Where: H = the internal heat production in the human body

E_d = the heat loss by water vapour diffusion through the skin

E_{sw} = the heat loss by evaporation of sweat from the surface of the skin

E_{re} = the latent respiration heat loss

L = the dry respiration heat loss

K = the heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing)

R = the heat loss by radiation from the outer surface of the clothed body

C = the heat loss by convection from the outer surface of the clothed body.

Fanger used the above equation and the results from climate chamber studies to derive a general comfort equation. Further to the general comfort equation, Fanger developed two comfort indices which are still widely used in thermal comfort research, these are the Predicted Mean Vote (PMV) and Percentage Predicted Dissatisfied (PPD). The PMV index allows the prediction of the thermal sensation of a group of people based on six key variables: air temperature, radiant temperature, air velocity, relative humidity, clothing insulation and activity level. However, the PMV index is not easy to interpret in practical cases as differences between individuals in the group mean that some may be more or less satisfied than others for any given PMV value (Fanger 1970). This led Fanger to develop the PPD index which describes specifically, the percentage of people in a group likely to be distinctly dissatisfied with their environment. These two indices, PMV and PPD, can be calculated in the following way (ISO 2005):

$$
\begin{aligned}
PMV = {} & \left[0.303 \cdot e^{(-0.036 \cdot M)} + 0.028\right] \\
& \cdot \Big\{(M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_a] - 0.42 \\
& \cdot [(M - W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) \\
& - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - \left(\bar{t}_r + 273\right)^4\right] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\Big\}
\end{aligned}
$$

$$
\begin{aligned}
t_{cl} = {} & 35.7 - 0.028 \cdot (M - W) - I_{cl} \\
& \cdot \Big\{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - \left(\bar{t}_r + 273\right)^4\right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\Big\}
\end{aligned}
$$

$$
h_c = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} & for \quad 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1\sqrt{v_{ar}} \\ 12.1\sqrt{v_{ar}} & for \quad 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1\sqrt{v_{ar}} \end{cases}
$$

$$
f_{cl} = \begin{cases} 1.00 + 1.290 I_{cl} & for \quad I_{cl} \leq 0.078 m^2 \cdot K/W \\ 1.05 + 0.645 I_{cl} & for \quad I_{cl} > 0.078 m^2 \cdot K/W \end{cases}
$$

$$
PPD = 100 - 95 \cdot e^{-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2}
$$

Where:

M = metabolic rate in watts per square metre (W/m^2)

W = effective mechanical power in watts per square metre (W/m^2)

I_{cl} = clothing insulation in square metres per kelvin per watt ($m^2 \cdot K/W$)

f_{cl} = clothing surface area factor

t_a = air temperature in degrees Celsius (°C)

$\bar{t}_r$ = mean radiant temperature in degrees Celsius (°C)

v_{ar} = relative air velocity in metres per second (m/s)

p_a = water vapour partial pressure in Pascals (Pa)

h_c = convective heat transfer coefficient in watts per square meter kelvin [W/(m^2·K)]
t_{cl} = clothing surface temperature in degrees Celsius (^{o}C)

NOTE: 1 metabolic unit = 1 met = 58.2 W/m^2; 1 clothing unit = 1 clo = 0.155 m^2· ^{o}C/W

2.2.1 Critique of the heat balance approach to thermal comfort

A number of criticisms of Fanger's heat balance approach to thermal comfort have emerged following further developments in the field. One such criticism arises from the fact that measurement of metabolic rate and clothing insulation in field studies are inevitably inaccurate (Chamra et al. 2003; Brager et al. 1993; ISO 2009). Furthermore, it was found that in order for thermal comfort models to be accurate, the effects of body motion and air movement must be included due to their strong influence on clothing insulation (Havenith et al. 2002). These criticisms refer to the model itself, either in terms of experimental methods or formulation of indices.

Perhaps the most significant criticism of the PMV/PPD model arises from the discrepancies observed between climate chamber studies used in the formulation of the model and field studies. This group of criticisms questions the ability of Fanger's model to accurately predict comfort temperatures. Numerous studies have found that peoples' comfort temperature in field studies, where contextual factors such as social acceptability and expectations are involved, can be significantly different to that predicted by the PMV model (Becker & Paciuk 2009; Humphreys & Nicol 2002; Loveday et al. 2002; Luo, Cao, Damiens, et al. 2014). Most significantly, the range of temperature at which people feel comfortable is far greater than can be accounted for by the model. This is most evident when considering field studies carried out in different climates where studies have often found that people in hot climates are able to feel comfortable at temperatures much higher than those from cold climates and higher than predicted by the PMV model (Humphreys & Nicol 1998; van Hoof 2008; Brager & de Dear 1998; Humphreys et al. 2016; Fountain et al. 1996). Furthermore, numerous studies have found that occupants of naturally ventilated buildings have a wider range of comfort temperatures than those of air conditioned buildings within the same climate context (Brager & de Dear 1998; van Hoof 2008; Taleghani et al. 2013; Humphreys & Nicol 1998; Busch 1992; de Dear et al. 1991). Thus, studies highlight the influence of local climate and personal experience, which are not included in the heat balance approaches, on individuals' thermal preferences.

2.3 Adaptive thermal comfort

In response to the criticisms of heat balance models, an alternative approach to thermal comfort, known as adaptive thermal comfort, has been set forward. This model is based primarily on results from *in situ* field studies and aims to consider the contextual factors that impact the acceptability of a given environment. The adaptive principle, which underlies this approach is that *"if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort"* (Nicol & Humphreys 2002). Thus, the fundamental difference between the adaptive approach and the heat balance approach (as described in Section 2.2) is that in the adaptive approach the occupant is not just a passive recipient of their environment but rather is actively involved in controlling it to maintain comfort. This conception of comfort as a dynamic system implies that significant deviation from neutrality is likely to result in discomfort while returning to neutrality is likely to result in satisfaction (Humphreys & Nicol 1998; Chatonnet & Cabanac 1965). This stems from results of various studies in differing climates where discrepancies had been observed between actual and expected comfort levels of field study participants based on Fanger's heat balance approach (Humphreys 1996); this was explained by the failure of heat balance approaches to account for the adaptive actions of the participants. Adaptive mechanisms can be broadly categorised into three types: behavioural, physiological and psychological (Brager & de Dear 1998).

Behavioural adjustments include actions that aim to improve the indoor climate or the thermal state of the body and can be personal (e.g. clothing and posture changes, activity, moving to different locations), technological (e.g. opening/closing windows or blinds, controlling fans or HVAC systems) or cultural (e.g. schedule adjustments or dress code) (Brager & de Dear 1998; Tweed et al. 2014). (In this regard, Fanger's PMV/PPD model can be seen as partially adaptive as it does account for clothing and metabolic rate (Yang et al. 2014).) Physiological adaptation includes all the physiological changes that result from the exposure to climate and that lead to greater tolerance towards the climatic conditions. Psychological adaptation refers to changed perception due to past experiences. Having lower indoor climate expectations results in occupants having greater tolerance to temperature fluctuations. All three of these mechanisms are closely linked which often makes them hard to unpick from one another. The following sections explore each of them separately though it should be noted that in almost all cases results can be explored through the lens of all three types of adaptive mechanism.

2.3.1 Physiological adaptation

Physiological adaptation, in the context of thermal comfort, relates to the many ways in which the body self regulates to maintain comfort under repeated exposure to thermal stress. These physiological mechanisms work to maintain thermal balance (homeostasis) in the body by balancing heat gains with heat losses. Heat gains come externally from the environment, and internally, as a product of metabolic function (Hanna & Tait 2015). Examples of these physiological mechanisms include metabolic heat production (e.g. through shivering), reduced skin blood flow and elevated basal metabolic rate under cold stress conditions and increased skin blood flow, sweating and reduced basal metabolism in heat stress conditions (Périard et al. 2015; Steegmann 2007; Taylor 2000). These mechanisms (among others) serve to regulate 5 key variables to within conditions conducive to physiological function while avoiding hazardous states. These 5 key variables are: mean body temperature, plasma osmolality, blood volume, central venous pressure and mean arterial pressure. These physiological mechanisms can be divided into two groups: genotypic adaptation which occurs of many generations and phenotypic which can occur within a generation (IUPS 2001).

Adaptation theory

Heat adaptation comes in two broad classes, acclimation and acclimatisation. Acclimation refers to adaptation resulting from artificially induced conditions such as experiments whereas acclimatisation refers to the adaptation resulting from natural exposure to thermal conditions (Taylor 2014). Acclimatisation is more complex than acclimation in the sense that is allows for behaviour to remove (or reduce) the stimulus to adapt resulting in variation in form and extent of adaptation compared to acclimation (Héroux et al. 1959). Adaptation can be morphological or functional. Morphological adaptation takes the form of anatomical changes whereas functional adaptation is seen in the operational characteristics of the system (Taylor 2014).

Whether or not a particular stress results in adaptation will be determined by its duration, frequency, variability and application frequency (Dill et al. 1964). Tipton et al. (2008) set out 6 key factors that determine adaptation responsiveness:

- Adaptation threshold – a stimuli must breach a critical threshold to induce adaptation.
- Adaptation latency – while stimuli may result in immediate effect on the homeostatic process, there will be a delay before adaptation is observed.
- Genetic influence – for any adaptation, there will be a maximum beyond which there will be significant adaptation resistance
- Response dynamics – the timescale for morphological and functional adaptation varies between individuals
- Size of adaptation impulse – response rates between individuals varies for the same stimulus strength
- Adaptation decay – after repeated exposure to a stimulus ends, the morphological and functional adaptation will gradually reverse.

Adaptation to hot and cold climates

Adaptation to hot environments has been studied more extensively (Taylor 2014; Taylor 2006; Hanna & Brown 1983; Hanna & Tait 2015) in comparison to cold adaptation (Steegmann 2007; Taylor 2006; Daanen & Van Marken Lichtenbelt 2016) with a focus on its implications for elite sports and more recently, the limits of human adaptability to climate change. The main cold adaptation responses are either insulative adaptations(e.g. increase in subcutaneous adipose layer, circulatory adjustments), metabolic adaptations (e.g. shivering) (Makinen 2010) or habituation (Castellani & Young 2016; Sawka et al. 2001). Habituation is the 'reduction of responses to or perception of a repeated stimulation' (IUPS 2001) resulting from periodic short term exposure and is the most common form of cold adaptation (Sawka et al. 2001). Adaptation to hot climates includes reduced core temperature, increased sweat rate and skin blood flow, lowered metabolic rate, reduced heart rate, improved fluid balance and increased thermal tolerance (Sawka et al. 2001). Exercise in heat is the most effective way to develop heat adaptation though some adaptation can be achieved through resting in the heat (Taylor 2006).

Taylor (2006) presents a comprehensive literature review of ethnic differences in hot and cold adaptation. However, as Taylor concludes, many of the studies have been conducted with small samples of indigenous populations in traditional habitats and without a structured approach. Furthermore, the focus on single adaptation responses may be misleading since genetic adaptation may result in whole system morphological changes which would not be ascertained by this type of study (Taylor 2006). These studies typically investigate a single, isolated adaptation response without consideration of the whole system. For example, studies of indigenous Australian Aboriginals, where night temperatures are regularly less than 5^{o}C, suggests hypothermic insulative acclimatisation observed through no decrease in metabolic rate and greater drop in body temperature, skin temperature and rectal temperature (Scholander et al. 1958). Insulative acclimatisation was also observed in Kalahari Bushmen where night temperatures were as low as 0^{o}C (Wyndham & Morrison 1958). In contrast, metabolic acclimatisation was observed in Alacaluf Indians of Tierra del Fuego where cold temperatures were regularly observed for 24 hours (Hammel 1960).

Early research into heat adaptation focussed on body size since it has an impact on heat exchange through both mass and surface area (Roberts 1953). Other specific heat adaptations in indigenous population that have been investigated include basal metabolism , sudomotor threshold (Wyndham et al. 1966; Wyndham et al. 1967; Fox et al. 1974), sudomotor capacity (Hwang & Baik 1997; Garcia et al. 1977; Kawahata & Sakamoto 1951), cutaneous vasomotor function (Thomson 1954; Katsuura et al. 1993; Fox et al. 1974) and endocrine function (Johnson et al. 1968; Macfarlane 1969; Fox et al. 1974; Mathew et al. 2001).

The studies discussed so far have investigated differences in adaptation between ethnic groups however, it remains unclear if the differences found are a result of genetic adaptation or long term acclimation (Taylor 2006). Acclimation to heat has been studied extensively in laboratory environments (and other artificial exposures) often for its implications for elite sports, however a full literature review is beyond the scope of this work. Some notable findings for heat acclimation include the fact that increased heat tolerance can be observed after only 5 – 14 days of exposure (Guy et al. 2015; Guy et al. 2016; Périard et al. 2015; Karlsen et al. 2015; Neal et al. 2016; Racinais et al. 2015) with the mechanisms responsible for the adaptation being changes in basal metabolic rate, plasma volume expansion, increased sweat rate, increased cutaneous blood flow and increased thermal tolerance (Burtscher et al. 2018). By comparison, cold acclimation has been studied far less extensively. Cold acclimation studies either involve exposure to cold air or cold water with a majority being carried out using cold water. Even small number of exposures to cold have been shown to reduce discomfort and delay and reduce shivering response (Makinen 2010). The type of cold acclimation depends on the duration of the exposure with exposures up to an hour causing habituation in the form of delayed shivering response (Makinen 2010) and longer exposures resulting in hypothermic habituation (Mathew et al. 1981).

Studies of indigenous populations have highlighted the acclimatisation potential in extreme conditions however, in modern societies, results are mixed. A study conducted in the Netherlands observed an increased response in metabolic rate in the winter compared with the summer (van Oojien et al. 2004) whereas a study conducted on a young urban dwelling sample in Finland found no evidence of cold acclimatisation (Mäkinen et al. 2004). Indeed, much of modern day human adaptation is likely to be behavioural (Makinen 2010; Tipton et al. 2008; Daanen & Van Marken Lichtenbelt 2016). Thermoregulatory behaviour studies have found that in moderate environments, skin temperature (not core temperature) is likely to be the most significant driver for regulatory behaviour (Schlader et al. 2013). Furthermore, it has been found that thermal sensation and thermal discomfort alone are capable of driving thermoregulatory behaviour; that is to say that a change in temperature is not required to instigate thermoregulatory behaviour (Schlader et al. 2011). In summary, research suggests that there may be differences in the physiological adaptation of ethnic groups though these have mostly been conducted in extreme conditions and with imperfect research design. Studies in modern societies have returned mixed results however there is extensive research to support acclimation in relatively short time scales.

2.3.2 Behavioural adaptation

Clothing adaptation is a fundamental mechanism by which occupants are able to achieve and maintain comfort in indoor environments by modifying personal variables. In some environments, like offices, occupants' adaptive opportunities can be limited by social conventions such as dress codes (Indraganti 2010). However, in residential settings, it can be assumed that occupants' are free to choose their clothing, and therefore level of thermal insulation, freely. Clothing is of course linked to culture and a number of studies have been conducted investigating specific practices in relation to traditional dress (Busch 1992; Indraganti 2010; Heidari & Sharples 2002).

Occupants are also able to take actions to change their environment in order to achieve comfort. Window opening is an essential mechanism by which indoor environments are maintained with it being found to be a favoured behavioural option in a number of different climate settings (Raja et al. 2001; Feriadi et al. 2003; Feriadi & Wong 2004; Wang et al. 2010a; Tweed et al. 2014; Kim et al. 2017). In hot climates, occupants of naturally ventilated buildings who make use of adaptive opportunities to open windows are found to have a wider range of comfort temperatures compared to those accustomed to air conditioning. In cold climates, adjusting thermostats is the primary method for adjusting the indoor environment during the heating season. Karjalainen (2009) found a relatively low level of engagement with thermostats in Finnish dwellings with participants reporting clothing adjustment being their primary adaptive action. However, discrepancies in occupants reported and actual responses to cold thermal discomfort have been found by Gauthier & Shipworth's (2015) field study which compared occupants' self-reported behaviour with a visual diary. This study found that occupants significantly overestimated their use of clothing as a response to cold thermal discomfort and suggests that other strategies may be being employed, such as heating use (Gauthier & Shipworth 2015).

A fundamental assumption of adaptive thermal comfort theory is that those with greater opportunities to adapt their environments to their preferences are less likely to suffer discomfort (de Dear & Brager 1998; Nicol & Humphreys 2002; Brager et al. 2004). This has been observed to be true in various studies (Mishra & Ramgopal 2013; Brager & de Dear 1998; Karjalainen 2009; Luo, Cao, Zhou, et al. 2014; Luo et al. 2015; Yun 2018). A study conducted by Luo et al. (2014) considered occupants from residential apartments who had different levels of personal control over their space heating systems due to the presence of a district heating system in some areas. The results of the study supported the adaptive model of thermal comfort as it found that those with greater control had a neutral temperature 2.6^{o}C lower than the group with no heating system control (Luo, Cao, Zhou, et al. 2014). Similar results were found by Zhang et al. (2010; 2013) with studies conducted in hot and humid climates where occupants of air conditioned buildings were found to maintain lower indoor temperatures and made use of adaptive opportunities earlier than those in naturally ventilated buildings. A further study conducted by Luo et al. (Luo et al. 2015) sought to investigate both the psychological and physical effects of availability of controls using a climate chamber study. The results showed that subjects expressed wanting to use personal controls during more extreme thermal conditions and furthermore that when controls were used, even slight improvements in actual conditions could lead to reduced reported discomfort (Luo et al. 2015). This conclusion relates personal control availability closely to psychological adaptation described in Section 2.3.3. These studies serve to provide evidence for the adaptive model of thermal comfort however there are also examples of studies that do not. One such example is presented by Goto et al.'s whose study of six office buildings in Japan with varying degrees of indoor temperature controls found no significant difference between the different groups (Goto et al. 2007).

In some cases there are obstructions to making full use of the available adaptive mechanisms that are unrelated to thermal comfort. In the case of window opening, common obstructions include: noise, privacy and security (Andersen et al. 2009; Laurent et al. 2017). In the case of space heating and cooling, cost can play a significant role in occupants' decision to heat at all as well as set point temperature selection (Tweed et al. 2014; Oreszczyn et al. 2006).

2.3.3 Psychological adaptation

In the context of adaptive comfort, psychological adaptation refers to the "*effects of cognitive and cultural variables and describes the extent to which habituation and expectation alter one's perception of and reaction to sensory information*" (Brager & de Dear 1998). Drawing on the rich field of psychophysics, a fundamental assumption is that repeated exposure to a stimulus reduces the intensity of the subjective response. Furthermore, psychological adaptation acknowledges a feedback loop between past experiences of thermal environments, indoor and outdoor, and the subjective assessment of current environments (Brager & de Dear 1998; Auliciems 1981).

Nikolopoulou & Steemers' (2003) investigation into understanding thermal comfort and psychological adaptation in outdoor spaces lists a number of parameters that make up psychological adaptation. Namely, naturalness, expectation, experience, time of exposure and perceived control (Nikolopoulou & Steemers 2003). Given the complexity of understanding these parameters and how they influence each other it is unsurprising that there is little to be said for how these mechanisms work, though as Nikolopoulou & Steemers conclude, greater understanding in this area would have significant implications for thermal comfort research overall (Nikolopoulou & Steemers 2003). Schweiker et al. (2016) have drawn on the field of psychology in the form of personality traits to explore the influence of individual differences on the use of indoor environmental controls. This study found a significant link between personality types and thermal sensation, thermal preference and self-efficacy (Schweiker et al. 2016).

2.3.4 Local climate

As Sections 2.3.2-2.3.3 have highlighted, adaptation to thermal environments is closely linked to the local climate. One of the key developments of the adaptive model was to understand comfort with relation to outdoor temperature, this can be expressed in the following way:

$$T_{comf} = A * T_{rm} + B$$

Where T_{comf} is comfort temperature (°C); T_{rm} is the exponentially weighted running mean outdoor temperature (°C); A, B are constants (Halawa & van Hoof 2012). The use of the exponentially weighted running mean outdoor temperature allows the model to take into account not only local climate but also introduces a time element. This is based on the premise that more recently experienced conditions are likely to have a stronger effect than those further in the past (Nicol et al. 2012). The exponentially weighted running mean can be expressed in the following way:

$$T_{rm} = (1 - \alpha)\{T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} + \cdots\}$$

where T_{od-1} is the daily mean outdoor temperature for the previous day, T_{od-2} is the daily mean outdoor temperature for the day before and so on and α is a constant (with a value between 0 and 1) which determines the response rate of the running mean temperature to outdoor temperature (Nicol et al. 2012). Most often, α is taken to be 0.8 (M. A. Humphreys et al. 2013) though the empirical basis remains unclear.

This understanding of comfort in relation to the outdoor climate came as a result of numerous field studies conducted in different climates. There are a number of review papers available which provide a comprehensive summary of global thermal comfort studies (Rupp et al. 2015; Kwong et al. 2014; Taleghani et al. 2013; Brager & de Dear 1998; Nicol 2017). Table 2.1 provides examples of the limited numbers of studies dwellings with information provided about the indoor and outdoor temperature during the study period as well as the comfort temperature. This sample of field studies highlights the diversity in comfort temperatures found in dwellings in different climates where occupants have control over their indoor environment.

2.3.5 Personal factors (gender, age, weight)

Some personal factors such as height and weight are widely understood to impact comfort conditions as they are directly related to the heat loss through the skin surface. Skin surface area is most often expressed in terms of the DuBois equation (ISO 2004):

$$A_{du}(m^2) = 0.202 m^{0.425} l^{0.725}$$

where m is the mass (kg) and l is the height (cm). However, other factors such as age and gender are less thoroughly understood. While studies suggest that school children express different thermal perception to adults and that further research is required to account for this in building standards (Teli et al. 2013; Teli et al. 2015) fewer studies have been conducted on adults of different ages to specifically discern differences in thermal preferences. Studies that have been conducted suggest that older subjects have slightly lower sensation votes than younger subjects explained by lower resting metabolic rate and more sedentary lifestyle (Indraganti & Rao 2010; Taylor et al. 1995).

Studies generally suggest that the difference in temperature preference between men and women is small and often due to clothing choice however there is some evidence that there may be significant differences between genders relating to both thermal preference and subsequent use of controls (Parsons 2002; Karjalainen 2012; Lu et al. 2018). Karjalainen (2007) found that women display a narrower band of thermal comfort compared to their male counterparts. That is to say that they feel uncomfortably cold or warm at higher or lower temperatures respectively than their male counterparts (Karjalainen 2007). Further to this, Karjalainen (2007) found that in a residential setting, male participants used thermostats more often than women. Similar results were observed by Wang (2006) whose study conducted in Harbin, north eastern China, concluded that women had a neutral operative temperature 1^{o}C higher than men and additionally that women were more sensitive to temperature variation that men. Kingma & van Marken Lichtenbelt's (2015) work suggests that the difference in metabolic rate between men and women may significantly affect the thermoneutral zone.

Table 2.1 Summary of indoor environment and thermal comfort field studies conducted in residential buildings with study details including comfort temperature (or neutral temperature), indoor temperature (T_{in}), outdoor temperature (T_{out}) and access to heating or air conditioning during the study. Empty cells are where the information was unavailable.

City (Country)	T_n or T_{com} (°C)	Sample size	Study details				Reference
			T_{in} (°C)	T_{out}(°C)	Heating	AC	
Jaipur (India)	30.15	426	29.8	27.6-35.7			(Dhaka et al. 2013)
Khabarovsk (Russia)	23.4	560	22.6	-19.5	✓		(Nicol 2017)
Harbin (China)	21.6-23.5	308	23.6-25.0	-10°C	✓		(Wang et al. 2017)
Dammam (Saudi Arabia)		17	22.5-31.6	35.4		✓ (some)	(Alshaikh & Roaf 2016)
Hainan (China)		1944	26.1	26.6			(Lu et al. 2018)
Seoul (South Korea)		24	27.5	26.5		✓ (some)	(Bae & Chun 2009)
		36	23.0	2.55	✓		
Darwin (Australia)	24.9-27.9	20	28.6	27.9		✓ (some)	(Daniel 2018)
Limasol & Paphos (Cyprus)		38	17.4	14.7	✓ (some)		(Pignatta et al. 2017)
Kuwait	25.2	111	22.7	37			(Al-Ajmi & Loveday 2010)
Sabrosa (Portugal)	15.3	141	17.5	7.0	✓ (some)		(Magalhães et al. 2016)
Braganca (Portugal)	15.9		17.4	7.6	✓ (some)		
Ponte de Lima(Portugal)	17.9		15.4	10.2	✓ (some)		
Porto (Portugal)	18.4		16	10.6	✓ (some)		
Leicester (UK)		249	18.5	2.3	✓		(Kane et al. 2015)

2.3.6 Critique of adaptive thermal comfort

The adaptive approach to thermal comfort has been criticised for being a 'black box' where the relationship between the adaptive mechanisms and the empirical findings are unclear (Nicol et al. 2012). Schweiker et al. (2012) highlight that thus far, little has been done to quantify the influence of the 3 different adaptive mechanisms. This is in part due to the typical methodology used to conduct field surveys which takes measurements of the indoor environments and participants subjective responses at particular times of day but do not record conditions specifically at times of interaction with controls (Schweiker et al. 2012). Schweiker et al.'s (2012) study suggests that it is possible to study behavioural, physiological and psychological adaptive mechanisms separately in a climate chamber setting.

Another specific criticism of adaptive thermal comfort is that it considers only indoor operative temperature while disregarding other variables such as metabolic rate, clothing insulation, relative humidity and air velocity which are known to impact thermal sensation (Fanger & Toftum 2002). Nicol and Humphreys (2002) argue that other parameters are related in some way to temperature and can therefore be excluded from the formulation of the adaptive model. However, Halawa & van Hoof (2012) point out that while this relationship may be true, it is yet to be clearly demonstrated. A further criticism set forward by Halawa and van Hoof (2012) is that the role of expectation supported by some thermal comfort researchers, lacks proper foundations. The example provided to highlight this is of over air conditioned spaces in hot climates which clearly fall outside the normal comfort range. If the 'expectation hypothesis' were true, Halawa and van Hoof (2012) argue that over time people would become accustomed to and therefore more tolerant of such conditions. This, however, does not seem to be the case in some situations such as over air conditioned spaces in very warm climates (Halawa & van Hoof 2012).

Not so much as a criticism but as a route to develop the adaptive model of thermal comfort, deDear has revived the concept of alliesthesia for understanding comfort in indoor environments (de Dear 2011). Alliesthesia is explained as (de Dear 2011):

> "...any external or environmental stimulus that has the prospect of restoring the regulated variable within the *milieu interieur* to its set-point will be perceived as pleasant (positive alliesthesia), while any environmental stimulus that will further displace the error between the regulated variable and its set-point will be perceived as distinctly unpleasant, or even noxious in more extreme cases (negative alliesthesia). Alliesthesia leads us to seek pleasant stimuli and avoid unpleasant ones."

In subsequent work, Parkinson et al. (Parkinson & de Dear 2015; Parkinson et al. 2016; Parkinson & de Dear 2016) have proposed framing thermal comfort as achieving thermal pleasure rather than as neutrality or acceptability. The notion that neutrality may not be the optimum for occupants has also been acknowledge by Humphreys et al. (2016).

2.4 Thermal comfort in a new climate

The previous section has outlined the fundamentals of adaptive thermal comfort theory from inception and including the key physiological, psychological and behavioural mechanisms underpinning it. This section will review research carried out investigating specifically the impact of moving from one climate to another on human thermal comfort. The critical consideration in the scenario of relocation is how adaptive mechanisms developed in one climate help or hinder comfort in a new environment.

2.4.1 Thermal history and adaptation

Despite the fact that adaptation is a fundamental aspect of adaptive thermal comfort theory, little research has addressed the nature of adaptation or the influence of thermal history on current preferences. The majority of the studies addressing thermal history have been conducted by Luo et al. in China and employ groups of participants moving from Northern China to Southern China (Luo, Ji, et al. 2016; Luo, de Dear, et al. 2016). A key factor in these studies is the availability of district heating in northern regions where the climate is described as 'severe cold'. In contrast, southern regions are not provided with district heating despite cold winter temperatures. The key findings from this group of chamber and field studies are:

- In addition to local climate, indoor thermal history influences thermal adaptation (Luo, Ji, et al. 2016; Luo, Zhou, et al. 2016)
- Occupants adapt more easily to neutral conditions than more severe conditions (Luo, de Dear, et al. 2016)

Chun et al.'s (2008) comparative study conducted in Japan and Korea employs both field study and chamber experiments to investigate short term thermal history. Participants were required to record a 'thermal diary' for 24 hours before completing a thermal comfort survey in a chamber where the environment was controlled at 28°C and 50% relative humidity. The findings suggest that thermal history, defined as "daily temperature exposures", influenced thermal sensation in relation to warm environments. Another chamber study where the ambient temperature was set at 30°C found indoor thermal history to influence thermal preference whereby participants from regions where air conditioning is pervasive reported greater discomfort (Kalmár 2016).

In addition to investigating the influence of thermal history, a small number of studies have considered time scales for adaptation or as Luo et al. (2016) refer to it, 're-adaptation' to a new climate. Currently, there is no consensus and studies have found evidence of adaptation in studies lasting from 9 days to nearly 4 years. These studies are summarised in Table 2.2.

Table 2.2 Summary table of studies investigating thermal adaptation

Adaptation time	Study type	Study information: Parameters measured	Study information: Details	Reference
9 days	Climate chamber	Skin temperature	Participants switched between 17°C and 37°C to investigate warmth acclimation.	(Pallubinsky et al. 2017)
10 days	Climate chamber	TSV, TCV, skin temperature, core temperature, brown adispose tissue etc.	Participants exposed to 15-16°C on 10 consecutive days with measurements taken before and after to investigate cold acclimation.	(van der Lans et al. 2013)
~ 4 years	Climate chamber	Sweat rate, skin and rectal temperature, heart rate, blood flow and pressure	Following a stabilisation period, 60 minutes of passive heating was induced through immersion of the lower legs in water at 42 °C.	(Wijayanto et al. 2012)
~1 year	Field study	TSV, TCV, clo	Comparison of long and short term Beijing residents, conducted in classrooms and offices.	(Cao et al. 2011)
~3 years	Field study	TSV, TCV, clo	Employed groups of participants who had been living in Shanghai for different periods. Conducted in teaching buildings.	(Luo, Zhou, et al. 2016)

TSV = thermal sensation vote
TCV = thermal comfort vote
clo = clothing insulation

2.4.2 Physiological adaptation

Yu et al.'s (2012) study investigated the difference in physiological responses between subjects accustomed to air conditioned and naturally ventilated indoor environments in 'heat shock' scenarios. To simulate heat shock, participants were moved from one 'neutral' climate chamber (26°C, 45% relative humidity) to a warm climate chamber (36°C, 45% relative humidity). With the small sample employed (10 in each group, air conditioned and naturally ventilated), Yu et al. (2012) found that those accustomed to naturally ventilated environments did not report feeling as hot or uncomfortable as the AC group. Furthermore, results indicated that sweat rates of the AC group varied and were found to be lower than that of the naturally ventilated group. Thus, the authors concluded that "long term exposure to different thermal environments can lead to difference levels of physiological acclimatisation" (Yu et al. 2012).

A further study by Yu et al. (2013) investigated the long term impact of access to indoor heating on levels of physiological response by considering sub groups from Shanghai and Beijing separately. This is based on Chinese legislation which stipulates that indoor heating systems be installed only if more than 90 days in the year see a mean air temperature of 5°C or less (Yu et al. 2013); Beijing does fall under this category and thus indoor heating is common whereas Shanghai does not. This study presented 2 significant findings: i) the skin temperature of the participants from Shanghai decreased faster than those from Beijing which indicates a greater degree of vasoconstriction and ii) participants from Beijing presented significantly more instances of shivering which implies that they require more extreme homeostatic mechanisms to maintain core body temperature (Yu et al. 2013). Since Shanghai experiences warmer winters than Beijing but therefore has no indoor heating, these findings suggest that indoor thermal history is more significant than outdoor thermal history in determining physiological acclimatisation (Yu et al. 2013).

2.4.3 Behavioural adaptation

Fuller & Bulkeley's (2013) qualitative study investigates the everyday behavioural mechanisms employed by British migrants to Spain to adapt to the warmer conditions. The authors found that people's expectations of a comfortable temperature changed with their new location; interviews revealed that temperatures that would have been considered warm in the UK feel cool in Spain (Fuller & Bulkeley 2013). Uptake of air conditioning was mixed with high users often using the lowest available temperature settings and other not having an air conditioning system installed at all (Fuller & Bulkeley 2013). Interestingly, Fuller and Bulkeley (2013) also found that people adjusted their daily routines to match the climatic conditions, in this instance that resulted in carrying out heat inducing chores, such as cooking and ironing, in the morning or evening.

2.4.4 Psychological adaptation

Luo et al. (2016) investigated thermal expectations of subjects from northern China, where district heating is common and southern China where there is no district heating. These two groups were then each divided again into two groups, those who had only lived in the same climate and those who had moved from one to the other. The resulting four groups were used to investigate the difference in thermal perceptions between those who have largely experienced moderate indoor environments (with district heating) and those who have not (no district heating) as well as how comfort perceptions change when moving from one to the other. The study indicated that there was no significant difference in thermal perception between those who have largely experienced moderate indoor environments and those who had not (Luo, de Dear, et al. 2016). Furthermore, it was found that those moving from the more extreme indoor conditions (with no district heating) to the more moderate conditions did so faster and with greater ease than those moving the other way (Luo, de Dear, et al. 2016). Although the authors explain these finding with respect to psychological adaptation, it is also possible that physiological adaptive processes also have an influence.

2.5 Standards for thermal comfort

A number of standards have been developed in order to help designers meet the comfort needs of occupants based on the thermal comfort models analysed above. The three most well-known and widely used are ASHRAE 55 (2013), ISO 7730 (2005) and CEN Standard EN15251 (CEN 2007). While other standards do exist, such as the Dutch Adaptive Temperature Limits guideline (ATG) (Taleghani et al. 2013) and the Chinese GB/T 50785 (Luo et al. 2015), they are not widely used and thus will not be focussed on here.

2.5.1 EN ISO 7730

The International Standard Organisation (ISO) sets out the method of calculation and use of the PMV/PPD index with criteria for local discomfort. The standard also provides a table of measured clothing insulation (clo) values of various common items of clothing along with metabolic rate (met) values for some typical activities. This standard sets out three categories of buildings based on the comfort conditions found within them where Category A has the smallest band of acceptable PMV and lowest threshold for both PPD and local discomfort followed by Categories B and C. The draught rating, a type of local discomfort, is the percentage of people predicted to be bothered by the draught. The full criteria for each building type is shown in Table 2.3.

Table 2.3 Specifications for Category A, B and C buildings in ISO 7730 where 'PPD' is the percentage predicted dissatisfied, 'PMV' is the predicted mean vote and 'DR' is the draught rating (ISO 2005)

Category	Thermal state of the body as a whole		Local discomfort			
	PPD %	PMV	DR %	PD % caused by		
				Vertical air temperature difference	Warm or cool floor	Radiant asymmetry
A	< 6	-0.2 < PMV < +0.2	< 10	< 3	<10	< 5
B	< 10	-0.5 < PMV < +0.5	< 20	<5	<10	< 5
C	< 15	-0.7 < PMV < +0.7	< 30	< 10	< 15	< 10

The ISO 7730 is accompanied by a number of supporting documents including:

- **BS EN ISO 7726.** Ergonomics of the thermal environment – Instruments for measure physical quantities (ISO 2001b)
- **BS EN ISO 8996.** Ergonomics of the thermal environment – Determination of metabolic rate (ISO 2004)
- **BS EN ISO 9920.** Ergonomics of the thermal environment – Estimation of the thermal insulation and evaporative resistance of a clothing ensemble (ISO 2009)
- **BS EN ISO 10551.** Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales (ISO 2001a)

2.5.2 ASHRAE 55

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard is sponsored by the American National Standards Institute (ANSI). Despite technically being a national standard, ASHRAE 55 is used globally due in part to the American dominance in the HVAC industry (Nicol et al. 2012). This standard is similar to ISO 7730 in that it is based on the PMV/PPD model however it does not adopt the categories laid out in ISO 7730. Unlike ISO 7730, the ASHRAE standard also includes an adaptive standard for 'naturally conditioned' buildings, which uses the relationship between outdoor temperature and indoor comfort temperature to determine acceptable zones for indoor temperature. This standard defines indoor temperature zones in which 80% or 90% of occupants are likely to find acceptable based on a comfort equation established from field studies compiled under the ASHRAE RP884 project (de Dear 1998). The comfort equation is expressed as follows (de Dear & Brager 2001):

$$T_{com}(°C) = 0.31T_o + 17.8$$

where T_{comf} is the optimal temperature for comfort and T_o is the mean outdoor temperature. The acceptable zone limits are then given by the following equation (de Dear & Brager 2001):

$$T_{accept}(°C) = 0.31T_o + 17.8 \pm T_{lim}$$

Where T_{accept} the limits of are acceptable zones and T_{lim} is the range of acceptable temperatures for 80 and 90 percent of occupants. The limits are $T_{lim}(80) = 3.5K$ and $T_{lim}(90) = 2.5K$ for 80 and 90 percent of occupants' satisfaction respectively; these limits are shown in Figure 2.1. ASHRAE 55 also provides a standardised 7-point scale of thermal sensation votes (TSV) which is widely used in thermal comfort surveys. This is shown in Table 2.4.

Table 2.4 Seven point ASHRAE thermal sensation scale (ASHRAE 2013)

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
-3	-2	-1	0	1	2	3

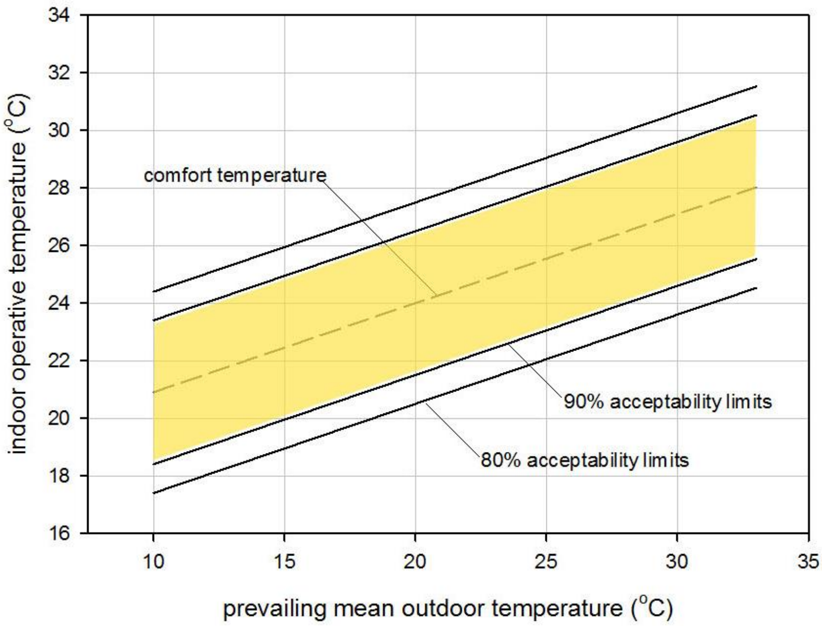


Figure 2.1 Acceptable operative temperature ranges for naturally ventilated spaces (ASHRAE 2013)

2.5.3 EN 15251

Based on results from the field studies conducted as part of the European Smart Controls and Thermal comfort (SCATs) project (Nicol & Humphreys 2010), the Comité Européen de Normalisation (CEN) presents the following equation for thermal comfort in naturally ventilated buildings:

$$T_{com} = 0.33T_{rm} + 18.8$$

where T_{comf} is the comfort temperature and T_{rm7} is the exponentially weighted running mean of the daily outdoor temperature. Where a long series of days is not available, this standard recommends using the mean temperature for the 7 previous days (CEN 2007). Like ASHRAE, this standard uses PMV-based criteria to provide acceptable limits of temperature deviation for free running buildings based on four categories of buildings; these categories are shown in Table 2.5.

Table 2.5 Applicability of building categories and their acceptable temperature ranges in free running mode from EN 15251 (CEN 2007; Nicol & Humphreys 2010; Taleghani et al. 2013)

Category	Explanation	Limit (T_{diff}, K)	Range of acceptability
I	High level of expectation only used for spaces occupied by very sensitive and fragile persons	±2	90%
II	Normal expectation for new buildings and renovations	±3	80%
III	Moderate expectation (used for existing buildings)	±4	65%
IV	Values outside the criteria for the above categories (only acceptable for limited periods)	±>4	<65%

2.6 Recommended winter indoor temperatures

In heated indoor spaces, guidance and standards provide recommended indoor temperatures based on the PMV model (CEN 2007; CIBSE 2015; ASHRAE 2013; ISO 2005; ISO 2017). In some cases, these are given as a single minimum value and sometimes as a range of temperatures. Furthermore, some are based on assumed values for clothing insulation and metabolic rate, such as in CIBSE (2015) and EN 15251(2007). In general, guidance for indoor temperatures is aimed at managing underheating in the winter and overheating in the summer. (2007)(2007)(2007)A summary of these recommended indoor temperatures is given in Table 2.6.

Table 2.6 Summary of design indoor temperature for dwellings

	Recommended indoor temperature		Assumptions
	Minimum temperature (^{o}C)	**Temperature range (^{o}C)**	
CIBSE			
Bedrooms	-	17.0 – 19.0	met: 0.9, clo: 2.5
Living rooms	-	22.0 – 23.0	met:1.1, clo 1.0
EN15251			
Category I	21.0	21.0 – 25.0	clo: 1.0
Category II	20.0	20.0 – 25.0	clo: 1.0
Category III	18.0	18.0 – 25.0	clo: 1.0
WHO			
Living rooms	21.0	-	
Other	18.0	-	
Public Health England	18.0	-	Appropriate clo

The Chartered Institute of Building Service Engineers (CIBSE) guidance gives a range of temperatures for bedrooms (17.0 – 19.0^{o}C) and living rooms (22.0 – 23.0^{o}C) with associated metabolic rate and clothing insulation values (CIBSE 2015). The EN15251 Guidance is based on the three building Categories described in Table 2.5 and provides 3 corresponding temperature ranges (CEN 2007). In contrast to this comfort driven approach to indoor temperatures, the World Health Organisation, based on health risk, advises a minimum temperature of 21.0^{o}C for living rooms and 18.0^{o}C for other spaces, such as bedrooms (WHO 2007). Similarly, Public Health England's (PHE) 'Cold Weather Plan' advises a minimum of 18.0^{o}C as a temperature that poses 'minimal health risk' and assumes suitable clothing is worn (PHE 2015).

All of these guidelines are based on the steady-state PMV model which was developed using studies carried out in the 1970's (Fanger 1970), as described in Section 2.2. Evidence suggests that indoor environments have changed in the intervening years (Utley & Shorrock 2008; Vadodaria et al. 2013) and therefore these standards may not represent the conditions in actual homes. A review of monitored indoor temperatures in UK homes indicates that is substantial variability in the actual indoor temperatures maintained with factors such as construction age and type and occupant age being significant (BRE 2013). Heating profiles and set points in English dwellings have also been found to vary significantly which is due to occupants interactions with building controls (Huebner et al. 2013a; Huebner et al. 2015; Huebner et al. 2013b) and is discussed further in the following Section.

2.7 Building energy performance

In recent years, there has been increasing industry concern about the difference in design and as-built energy performance of buildings (Zero Carbon Hub 2014; Carbon Trust 2011). While some discrepancy is inevitable due to calculation errors in models and simulations, a degree of similarity is necessary for reliable performance (de Wilde 2014). Broadly speaking, the performance gap can be attributed to three factors; (i) design assumptions and modelling, (ii) construction and build quality and (iii) users (including management) (Menezes et al. 2012). Furthermore, it is evident that as technological advances lead to improved energy efficiency with respect to building fabric, there is a greater risk of performance gap as user behaviour contributes more significantly to overall energy use (Ioannou & Itard 2015; De Meester et al. 2013).

Research aimed at reducing the performance gap has largely focussed on either improving the design assumptions by better understanding occupants and behaviour (Mahdavi & Tahmasebi 2015; Kane et al. 2015; Motuziene & Vilutiene 2013; Bonte et al. 2014) or investigating approaches that allow user feedback and interaction to facilitate a smooth transition to occupancy (BSRIA 2014; Way & Bordass 2005; Menezes et al. 2012; Day & Gunderson 2014). These studies together highlight that occupants can have a significant role in determining the performance of buildings since they are not merely passive receivers of design strategies (Grandclément et al. 2014; D'Oca et al. 2014). Often, user behaviour is driven by achieving overall comfort and studies have found that thermal comfort is the most significant factor in this (Gossauer & Wagner 2011; Frontczak & Wargocki 2011; Frontczak et al. 2012). Numerous studies have investigated the contribution of occupant behaviour on energy use and have found it to be significant, though the degree of significance varies from study to study (Andersen et al. 2009; Bonte et al. 2014; Kane et al. 2015; Maier et al. 2009; Fabi et al. 2012; Gram-Hanssen 2010; Yousefi et al. 2017).

2.7.1 Occupant behaviour

This section will review literature pertaining to occupant behaviour in more detail. It will focus on window and heater use in domestic settings as these are the key mechanisms for controlling indoor environments in the UK context.

Window use in residential settings

Window use behaviour is closely linked to local climate as different behavioural will result in different effects on the indoor environment depending on the climate. Therefore, this review will focus on studies investigating window use behaviour in temperate climates similar to the UK. Andersen et al.'s (2009; 2013) work on window opening behaviour in Danish households found that CO_2 concentration and outdoor temperature were the most important variables determining interactions with windows. In terms of environmental drivers, indoor air temperature has also been cited as a driver for window opening with a substantial increase in probability of opening over 20^{o}C (Raja et al. 2001; Stazi et al. 2017) though this has been observed in office buildings. Fabi et al. (2012) and Calì et al. (2016) found time of day to be the most common driver for window opening and the second most common for window closing. This is likely to be due to typical activities carried out at certain times of day e.g. showering and cooking (Stazi et al. 2017). Bedrooms have been found to be the highest ventilation zones even during the winter with orientation also playing a role in probability and duration of opening (Dubrul 1988).

Studies have found window use to have a significant impact on energy consumption (Laurent et al. 2017; Wang & Greenberg 2015; D'Oca et al. 2014) though quantifying this remains challenging. Laurent et al.'s (2017) study conducted in a non air-conditioned dormitory in the US found window opening patterns to have a significant influence on energy consumption (with an annual error ranging from 0.2% to 10%). No studies quantifying the energy implications specifically resulting from window use behaviour in UK dwellings were found.

Heater use in residential settings

Indoor space heating is the greatest source of energy demand in UK dwellings (Palmer & Cooper 2012) making user interaction with controls an important area of research for building energy simulation. Huebner et al.'s work looking at heating practices and indoor temperatures in English homes found substantial variability in both temperature set point and heating hours (Huebner et al. 2013b; Huebner et al. 2013a; Huebner et al. 2015; Shipworth et al. 2010). On average, indoor temperatures were lower than the typical model assumption of 21^{o}C by 1.5^{o}C (Huebner et al. 2013a) where 82.7% of the sample were owner occupied households (Huebner et al. 2013b). Furthermore, weekend heating patterns were found to be closer to typical weekday assumptions than suggested by guidelines (Huebner et al. 2013a).

A number of drivers for space heating use have been identified which like window use behaviour can be linked to the environment and the occupants, among other things (Wei et al. 2014). In the UK, outdoor temperature has been found to be related to space heating as well as solar radiation, home ownership and perceptions of the indoor environment (Andersen et al. 2009; Wei et al. 2014; Engvall et al. 2014). Gill et al.'s (2010) UK based study estimated that energy related behaviours can account for 51% of space heating demand and Gram-Hassan (2010) found a 3 fold difference based on behaviour in UK dwellings.

2.8 Summary

The literature review has provided some background and insight into the development of thermal comfort research to date. The theoretical understanding of thermal comfort has shifted from a steady state heat balance approach to an adaptive approach following an inability of the former to fully explain the empirical data. The adaptive approach however, is not without weaknesses. While the concepts of physiological, behavioural and psychological adaptation are embedded in the theory, there is a lack of understanding with regard to the underlying mechanisms at work. Physiological studies offer insight into the ability to adapt or readapt to new environments and suggest that this is possible in relatively short periods of time. However, few field studies have focussed on peoples' adaptive capabilities in a new climate given the freedom to choose their preferred environment. Furthermore, those that have been conducted are largely in offices or teaching buildings and not residential settings where occupants are likely to have greater control over their indoor environment. This work will aim to shed light on thermal preferences and adaptation in residential settings in a new climate and assess the energy performance implications of occupants with diverse thermal histories.

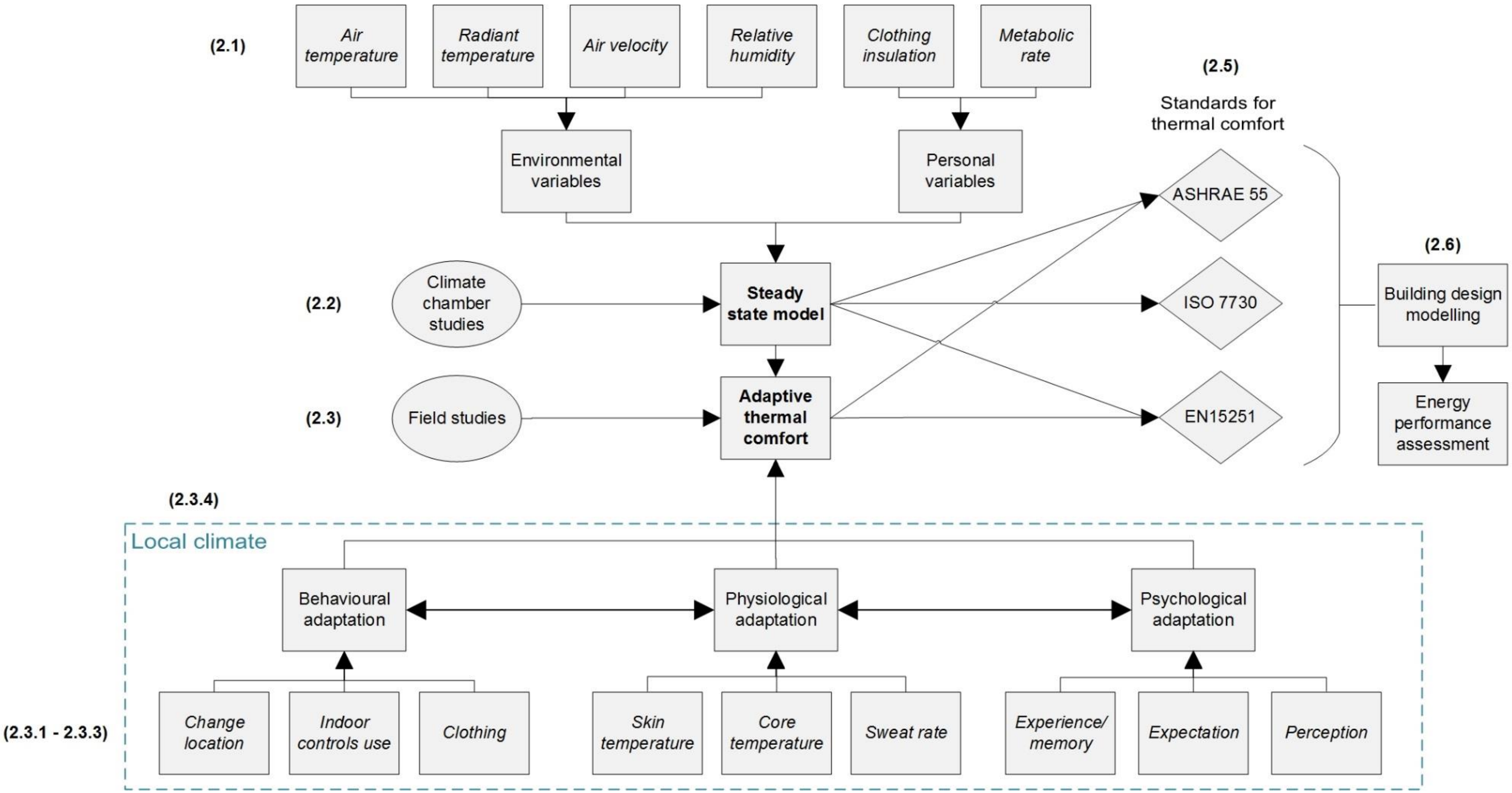


Figure 2.2 Summary of literature review. This work aims to investigate the impact of relocation, or changing the blue 'local climate' box on thermal comfort and energy performance.

Chapter 3

Research Design

This section presents the approach used for this research starting with a review of common methods in the field of thermal comfort. Then, a description of the pilot study, larger scale face-to-face study and individual profile app-based study are outlined including the instruments used. Also outlined is the energy simulation method used to assess the energy implications of diversity in indoor thermal preferences. The section concludes with the ethical considerations associated with this work.

3.1 Review of methods

This section provides an overview of commonly used methods for thermal comfort studies including overall design (transverse and longitudinal studies), questionnaire design and subjective response scales, indoor measurements and analysis methods.

3.1.1 Thermal comfort studies

Studies investigating thermal adaptation have typically involved assessment of thermal comfort through subjective responses to the environmental conditions alongside measurements of indoor environmental parameters (de Dear 2004). Studies are either conducted in climate chambers, where the environmental conditions are highly controlled, or in participants' typical surroundings (field studies). Climate chamber studies have the benefit of control over clothing insulation and metabolic rate, as well as the indoor environment, which have been found to have the greatest influence on PMV (Gauthier & Shipworth 2012). However, participants' ability to take adaptive actions such as open windows or change clothing level, are determined by the study design in climate chamber studies and are often not representative of real-life behaviour. Furthermore, climate chamber studies typically employ small samples that are unrepresentative of the population at large (de Dear 1998). Examples of climate chamber studies investigating thermal adaptation in a new climate have been outlined in Section 2.3.6 (Yu et al. 2012; Luo, Ji, et al. 2016). While this type of study provides useful insight into adaptation, the controlled conditions do not provide a realistic representation of people's behaviour and preferences (de Dear & Brager 1998; de Dear 1998).

Field studies, in contrast, allow participants to be studied in familiar settings with a wider range of adaptive mechanisms available though they can be more time consuming to conduct. In particular, residential field studies into thermal comfort are challenging due to the time needed to acquire large sample sizes and requirement of longer term engagement from participants. Subsequently, most field studies are conducted in offices where a large number of people can be surveyed simultaneously. Field studies can either be transverse or longitudinal; transverse surveys use all (or a large part) of the selected population to ensure that the results will be representative (Nicol et al. 2012). They also have the benefit of causing a low level of intrusion to participants. Longitudinal studies involve repeated surveying of a smaller group of the selected population (Nicol et al. 2012). This type of study is often limited by the number of volunteers as they tend to require greater involvement from participants. Therefore, sample sizes tend to be smaller though they provide more information about the individuals involved. Longitudinal studies also allow comparison of people over time due to the repeated surveys (Humphreys et al. 2016).

Questionnaires

Assessment of thermal comfort requires subjective responses from participants on their perceptions of the indoor environment. Typically, studies follow the guidelines set out in standards, such as ISO 10551 and ASHRAE (ISO 2001a; ASHRAE 2013), and follow the same (or similar) wording as other studies, such as the questionnaire used in the SCATs study (McCartney & Nicol 2002), for comparison with other research. This provides guidance on both the question and the response options given in the form of subjective scales such as that shown in Table 2.4 on page 23. Recent research has started to question them on the grounds of their validity. Humphreys et al. (2016) highlight issues surrounding the translation of scales into other languages where cultural meaning can have an influence on the way in which participants respond. Schweiker et al.'s (2017) work has presented reasons to question the assumption that points on the descriptive comfort scale are equidistant. This non-linear relationship between temperature and sensation is likely to have significant implications for the way in which results of thermal comfort studies are understood, though there is no current concensus on how best to deal with this. Schweiker et al. (2017) also found that respondents perception of the 'comfort range' on the ASHRAE scale differed greatly. However, these scales are still widely used and are considered best practice in thermal comfort research and were therefore used in this study. This allowed for comparison with other studies and compliance with international guidelines.

In addition to questions directly relating to occupant's perceptions of the indoor environment, many studies include background questionnaires to acquire further information on the study participants. Questionnaire design and delivery is the topic of substantial work in the field of social science with a number of key guidance documents widely available (Bryman 2016; Oppenheim 1992; Leeuw et al. 2008). Questions can either be closed, resulting in quantitative data, or open, resulting in qualitative data. Quantitative survey responses can lead to more straightforward analysis however, qualitatative questions can be used to provide a fuller picture of subjective opinions (completeness) and provide explanations to unexpected findings in quantitative data (explanation) (Bryman 2006).

Indoor environmental parameters

In field studies, measurement of indoor environmental parameters are usually taken using a sensing station which includes devices to measure air temperature, radiant (or globe) temperature, air velocity and relative humidity. Specifications for manufacturers and users of instruments to record environmental parameters are provided in ISO 7726 (2001b). Increasingly, studies are employing temperature and relative humidity monitoring devices in place of sensing stations due to lower cost and less disturbance to participants. Crucially, when combined with self-reporting of subjective responses, they also allow for longer term assessment of thermal comfort than simple on the spot surveys where the researcher's presence is required.

Clothing and metabolic rate

In field studies of thermal comfort, clothing level is usually either estimated by the researcher based on visual inspection or self-reported by the participants using a checklist of standard items. These are then matched to clothing insulation values provided in ASHRAE 55 (2013) and ISO 9920 (2009) standards. This method can lead to substantial errors in clothing insulation value (Chamra et al. 2003; Brager et al. 1993) however the simplicity of this method makes it appealing in field studies (Nicol et al. 2012; Gauthier & Shipworth 2012). ISO 8996 (2004) provides four levels for the determination of metabolic rate in accuracy and risk of error. A greater degree of accuracy requires measurements of specific parameters related to metabolic rate such as heart rate (Level 3) or oxygen consumption (Level 4) (ISO 2004).

3.1.2 Analysis methods for thermal comfort responses

This study aimed to investigate differences in thermal preferences of occupants with different thermal histories which requires a method for estimating comfort temperatures as well as statistical methods for comparison. A full review of statistical methods is beyond the scope of this work though a number of comprehensive guides are widely available (Field et al. 2012). Commonly used methods in thermal comfort include linear and logistic regression, means tests such as ANOVA and non-parametric test such as Chi-squared or Fisher exact (Field et al. 2012).

Nicol, Humphreys and Roaf, in the first two books of a three part series, present a comprehensive account of common thermal comfort analysis methods (Nicol et al. 2012; Humphreys et al. 2016). Basic analysis can be conducted easily by plotting variables against each other, a key plot includes comfort vote against indoor operative temperature. The linear regression of this plot, where comfort vote is the dependent variable, produces an equation of the form:

$$C = a + bT_{op}$$

where C is the predicted comfort vote, a is the y-axis intercept and b is the slope of the regression line (Nicol et al. 2012). Where $C = 0$ (or 4, if the ASHRAE scale is given as 1 to 7 rather than -3 to 3), is said to be the neutral temperature of the sample.

Griffiths method

Statistical analysis methods to determine comfort temperatures, like those described above, rely on large sample sizes to be meaningful. Griffiths (1990) introduced a method for determining comfort temperature in studies where sample sizes are small. This method linearly adjusts the actual temperature by an amount that represents the distance of the comfort vote to a neutral response (0). In Griffiths' original report, each point on the 9-point comfort scale represented 2.33K (Griffiths 1990). Since then, the convention has been to use a 7-point comfort scale which translates to 3K for each point (Nicol et al. 2012). This simple method has been developed by Nicol et al. (2012) who present this approach as a linear relationship between operative temperature and comfort vote, with the slope being equivalent to the regression coefficient (Nicol et al. 2012). The slope, or Griffiths coefficient G (K^{-1}), assumes that no adaptation has taken place. The Griffiths slope has been found most likely to be 0.5 (Humphreys et al. 2010; Nicol et al. 2012) resulting in the following equation determining comfort temperature in small samples:

$$T_{com} = T_{op} - \frac{TSV}{0.5}$$

Where T_{com} is the comfort temperature, T_{op} is the operative temperature and TSV is the thermal sensation vote on a 7-point ASHRAE scale. The Griffiths method was used in this study as the sample sizes are modest due to the longitudinal survey design and the limitations posed by conducting field work in residential settings.

Critique of the Griffiths method

The Griffiths' method main appeal is that it provides a way to analyse small samples which the statistical methods do not. However, it is not without problems. The assumed Griffiths coefficient of 0.5 was initially selected arbitrarily but has since been validated by Humphreys (2013; 2007) and others (Teli et al. 2015). However, the level of validation does not match the level of use of the method and the value has been challenged by other authors (Schweiker et al. 2013; de Dear et al. 2013). De Dear et al. (2013) suggest an estimated value of 0.29 based on Fanger's PMV/PPD model and estimated clothing insulation, metabolic rate, relative air speed and relative humidity. Rijal et al.'s (2008) field study in Pakistan found an R value of 0.5. Schweiker et al. (2013) demonstrated that the value used for the Griffiths coefficient to have a strong influence in a climate chamber study with behavioural interactions enabled. In summary, a suitable value for the Griffiths coefficient (R) remains contentious. Furthermore, the Griffiths method assumes the ASHRAE thermal sensation scale to be linear such that T_g is transposed the same amount for each incremental difference in thermal sensation vote. However, Schweiker et al. (2017) found that most people do not consider the points on the ASHRAE scale to be equidistant. Evidence suggests that people do not interpret ASHRAE scales uniformly and that this affects assessment of thermal comfort (Schweiker et al. 2017; Fuchs et al. 2018).

Furthermore, the Griffiths method takes no account of the subjective response to thermal preference (voted on a 5-point scale). The response options for this question are: Much cooler, a bit cooler, no change, a bit warmer or much warmer. In instances where the subject responds with 'no change' it would be intuitive to override any transformation of T_{op} and retain this value as the comfort temperature. However, the Griffiths method does not do so. This is somewhat an artefact of the language used in Thermal Sensation Vote scale whereby a response of 'Slightly Warm' (5) or 'Warm' (6) may be considered a good thing during the winter and may be providing optimal comfort for subjects (Schakib-Ektaban et al. 2018). If then a subject responds 'No change' on the thermal preference question, there could be an opportunity to account for this. Despite these shortcomings, this method has been used due to its appropriateness for small sample sizes and since it used across all datasets, comparison should not affected significantly. However, future work of the research community may seek to address these challenges.

3.2 Case Study: Mayflower Halls of Residence Complex

The case study building is the University of Southampton's newly built Mayflower Halls of Residence complex. First occupied in October 2014, the complex provides 1104 accommodation rooms most of which are single ensuite rooms arranged in cluster flats with shared kitchen/living room although some studio flats and 1-bedroom flats are also available. Facilities available on site include laundry room, cycle store, gym, study area, common rooms and a convenience store. Space heating is provided to all accommodation rooms by a district heating network and rent payment includes a flat rate for all services. The layout of the three buildings that comprise the complex are overlaid on a map in Figure 3.1. The complex is located in central Southampton close to the retail district and train station.

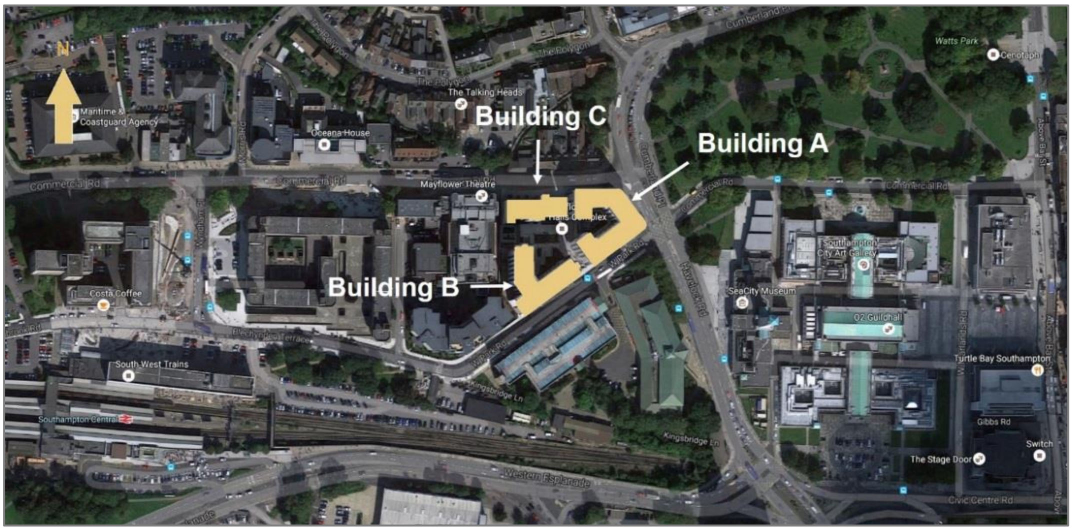


Figure 3.1 Map showing location and schematic outline of Mayflower halls of residence complex (Google Earth 2016)

Southampton is located on the South coast of England, approximated 120 km from London, as shown in Figure 3.3. The climate is classified as Cfb, warm temperate, according to the Köppen-Geiger classification system (Kottek et al. 2006). Figure 3.2 shows a summary of the climatic conditions in Southampton based on the period between 1981 and 2010 (Met Office n.d.).

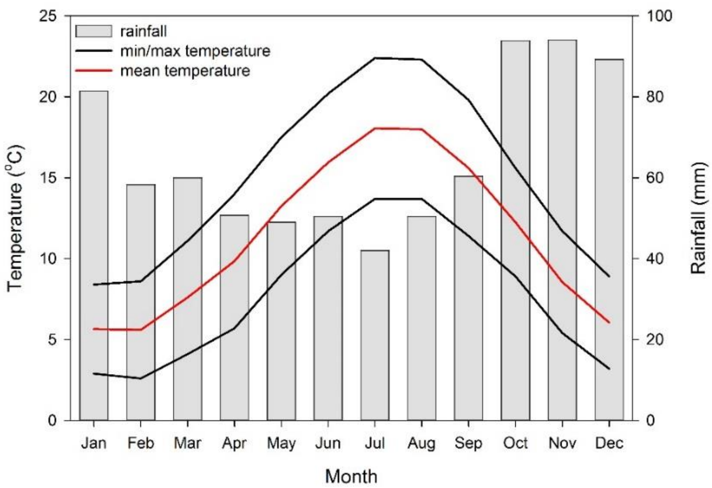


Figure 3.2 Southampton weather data for period between 1981-2010 including daily mean maximum, minimum and mean temperature and rainfall (Met Office n.d.)

Figure 3.3 Map showing location of Southampton relative to London

Figure 3.4 shows images of various facades of Mayflower halls complex including the northeast (top left), internal facing east and northwest (bottom left) and south east (right). Figure 3.5 shows schematic plans of typical accommodation units in Mayflower Halls. Each resident has access to controls which should enable them to maintain their indoor environment to suit their preferences. These include curtains, top opening tilt windows with trickle vents (Figure 3.6; left) and individual radiator valve with settings 0 to 5 (Figure 3.6; right).

Figure 3.4 Photographs of Mayflower Halls of residence facades. Top left: North-East facade, right: South-East facade, bottom left:courtyard and internal East and North West facades

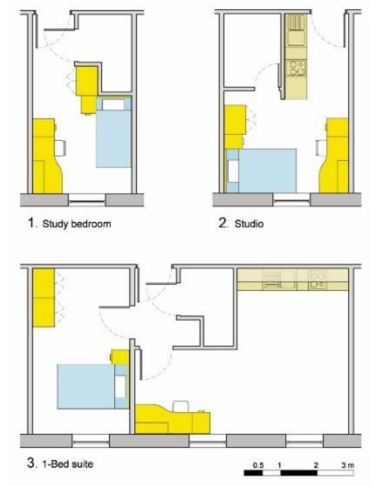


Figure 3.5 Schematic plans showing typical layout of accommodation rooms in Mayflower halls of residence

Figure 3.6 Photographs of indoor environmental controls available to Mayflower residents; thermostatic radiator control valve (left), top opening tilt window with trickle vent (right)

This site was chosen as a case study for a number of reasons:

- **Quality & design**. The recentness of the construction provided a guarantee of adherence to current building regulations. Furthermore, the similarity in design of each accommodation unit allowed for straightforward comparison of occupants as differences in building characteristics become negligible. Typically, building characteristic would have a strong influence of comfort preferences and practices and the subsequent study design.

- **International residents**. The likelihood of a large proportion of student residents arriving from different climates was high given the large number of international students studying at the University of Southampton. Having study participants who have recently arrived in the UK from their home climate was essential for this research project.

3.3 Pilot Study

A pilot study was devised to gain some initial understanding of the research topic to be addressed and to guide the methodological approach. In particular, it provided an opportunity to test the initial hypothesis, that an occupant's previous climate has an influence on the thermal preference and adaptation in a new climate. It also provided an initial understanding of perceptions of the building and differences between individual occupants. In terms of methodology, it allowed examination of the appropriateness of the case study building and testing of the questionnaire and equipment.

3.3.1 Study design

In order to investigate the influence of thermal history on indoor environmental preferences, a mixed methods approach was developed. Quantitative data collected included long term temperature and relative humidity monitoring, on the spot measurements of indoor environmental parameters and structured survey responses. The qualitative data collected includes a few open ended questions for the sake of completeness and explanation. Local weather data from Southampton docks was acquired from Weather Underground (weatherunderground 2016).

The study can be divided into three major sections with a timeline provided in Figure 3.7:

- **Indoor environmental monitoring.** Long term, high resolution monitoring of indoor air temperature and relative humidity. This allowed for analysis of the actual conditions kept in individual rooms.

- **Online Post Occupancy Evaluation (POE) survey**. Sent to all residents of the case study, this provided a broader picture of attitudes to the indoor environment and the use of indoor environmental controls.

- **Thermal comfort survey**. Face-to-face thermal comfort survey accompanied by on the spot measurement of air temperature, radiant temperature, relative humidity and air velocity. This provided information on occupants' preferences for the indoor environment. In the interest of completeness, the survey questionnaire also included the questions in the online POE survey.

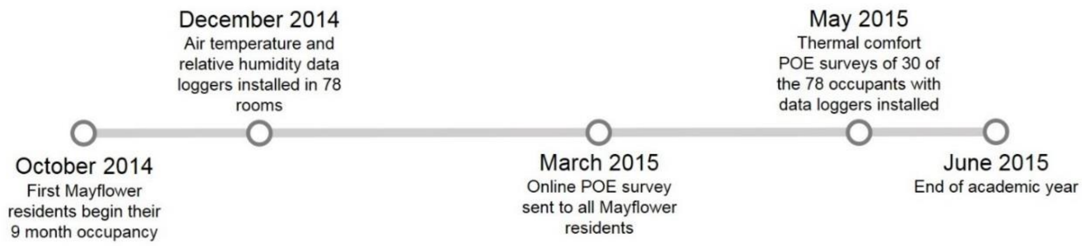


Figure 3.7 Pilot study timeline

Sampling & Recruitment

Quota sampling was used to select occupants for the long term monitoring required for the POE. Selection was based on room level and orientation in order to provide a representative sample and resulted in 78 volunteers. Convenience sampling was used to provide the sample for the face-to-face surveys. The 78 participants of the existing monitoring study formed the sampling frame. Invitation to participate in a face-to-face questionnaire survey was by email; those who did not wish to participate in the face-to-face survey were sent the iSurvey link to the online POE survey. Incentives were offered to the 78 participants invited to carry out the face-to-face survey in the form of a chance to win one of three £50 Amazon vouchers. No incentives were offered to the online survey participants.

3.3.2 Questionnaire design

The POE section of the questionnaire was adapted from Blyth et al.'s (2006) 'Guide to Post Occupancy Evaluation' to make it suitable for domestic buildings. The POE survey included questions relating to:

- **Personal details.** Age, gender, level of study, country of residence prior to Mayflower Halls
- **General use**. Occupancy hours, satisfaction with various spaces, facilities, location, feedback reporting
- **Indoor environment.** Subjective assessment of indoor environment (temperature, air movement, lighting, noise etc.)
- **Use of controls**. Heater, windows etc.

A full questionnaire can be found in Appendix B - I. Most of the questions employ Likert –scale type responses, in order to ensure a greater degree of clarity in responses, participants must be able to clearly understand the meaning of each point on the scale (Krosnick & Presser 2010). Furthermore, reliability of results requires a uniform interpretation of the meaning of scale points amongst participants (Krosnick & Presser 2010). This is a particular challenge in this case where language skills of the participants with English as a second language is likely to differ both between each other and with native English speakers. Given these considerations, a 5 point, rather than 7 point, scale was used.

Assessment of thermal comfort follower the format and wording of the questions and response options follows those used in the SCATs project (McCartney & Nicol 2002) and is also similar to the guidelines in ISO 10551(2001a). Importantly, the wording of the question stressed that responses should refer to participants current sensation and the response options closely match. Clothing insulation was estimated by the researcher by visual inspection. Metabolic rate was estimated by reported activity level of the participant for the 30 minutes prior to the survey. In cases where more than one activity was reported, a time weighted average was taken. This corresponds to a Level 2 assessment according to ISO 8996 (2004).

3.3.3 Review

The pilot study provided some useful insights into the challenges and opportunities in this research and guided the development of the methodology for the in-depth study.

- **Scheduling.** Since this pilot study was the lead researcher's first experience of conducting surveys, it provided invaluable experience and practical information such as the approximate time for each visit. Subsequent visits involved a shorter questionnaire due to the lack of POE related questions however since the globe thermometer requires a minimum of 20 minutes in each room (15-minute reaction time), the scheduling of survey visits was modified to reduce disruption to the participants.

- **Indoor thermal history**. The results from the initial analysis of the pilot study highlighted that indoor thermal history and heating practices are crucial to understanding occupant preferences in a new climate. Therefore, additional questions were added to the next round of surveys relating specifically to heating/cooling systems and practices in occupant's previous climates.

- **Repeated measurements.** The pilot study demonstrated the need for multiple comfort surveys over the course of the year of occupancy. While this was expected, the study highlighted this requirement as well as the need to conduct the first survey as close to the start of the occupancy possible.

- **Self-reporting.** The questionnaire requires participants to recall and report their behaviour with regards to frequency of indoor environmental controls use. Self-reporting is known to be problematic due to both recall errors and response bias (Leeuw et al. 2008). The final round of surveys relies less on participant recall for information about controls use but instead provides a number of 'snapshots' of the current state of controls.

3.4 Face-to-face study

3.4.1 Study design

This longitudinal study drew on many of the data collection methods employed in the pilot study. Long term monitoring of temperature and humidity, thermal comfort surveys and questionnaires were all utilised in the same way through this phase of the study. Additionally, participants were asked to keep a thermal comfort log sheet. This asked participants to note the time, date and a comfort vote on a 7-point scale; a sample is included in Appendix B - III. This allowed additional estimations of comfort temperature when matched with the corresponding air temperature from the data loggers. While the temperature would ideally be a measurement of globe temperature, equipment comparison tests found that the air temperature loggers closely matched the globe temperature sensor (Section 3.6.2) making it a suitable proxy. Mayflower halls was again used as a case study for reasons outlined in Section 3.2.

To study thermal adaptation to a new climate, the pilot study highlighted the importance of a number of thermal comfort surveys over the course of the initial occupancy period. This allows consideration of changing preferences over time. A major risk for long term studies where participants are required to conduct more than one survey is drop-out rate. Therefore, the number of surveys across the study period was limited by willingness to participate and was therefore set at four. A timeline for the study is shown in Figure 3.8.

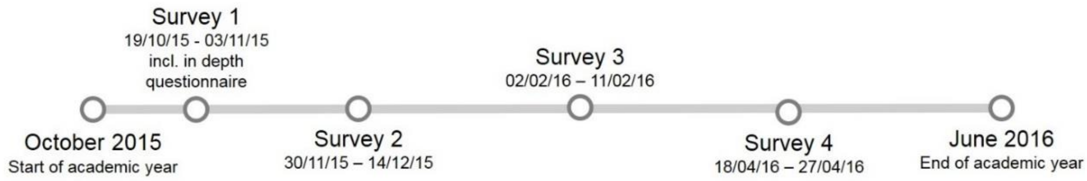


Figure 3.8 Face-to-face study timeline

Sampling & Recruitment

Convenience sampling was used for the in-depth study with the sampling frame being all residents of Mayflower halls. However, due to time constraints and the number of planned surveys, the maximum sample was limited to 60 participants, based on a reasonable estimation of time per survey. In order to maximise the number of participants from climates other than the UK, a limit of 20 was set on the UK participants. Any volunteers after the first 20 were placed on a waiting list in case of any non-response or missed appointments. This could loosely be described as a form of purposive sampling employed in qualitative studies (Bryman 2016).

Participants were contacted initially by email with a short description of the study, details on participation and invitation to meet the researcher before agreeing to participate. Those who opted in to the study were then emailed a link to a Doodle Poll (online planning tool) where they could select a two hour time slot for the initial survey and data logger installation. A detailed recruitment protocol is provided in Appendix C - I. Incentives were offered for participation in the form of a £20 Amazon voucher for participants who completed all four questionnaires.

3.4.2 Questionnaire design

Like the pilot study, the first of the four questionnaires included, as well as standard thermal comfort survey questions as described in Section 3.3.2, questions relating to participants personal details. This section was modified to include questions relating to participants heating and cooling practices in their previous residence. The questions relating to thermal comfort assessment were based on those used in the SCATs database (McCartney & Nicol 2002) and closely matched ISO (2001a)and ASHRAE (2013) guidelines as well as the pilot study to allow for straightforward comparison. Importantly, the wording of the question stressed that responses should refer to participants current sensation and the response options closely match. Clothing insulation was estimated by the researcher by visual inspection. Metabolic rate was estimated by reported activity level of the participant for the 30 minutes prior to the survey. In cases where more than one activity was reported, a time weighted average was taken. This corresponds to a Level 2 assessment according to ISO 8996 (2004).The full questionnaire can be found in Appendix B - II.

3.4.3 Review

The methodology for the in-depth study, developed with insights from the pilot study, provided valuable information both with regards to fulfilling the research aims and shaping the future methodology.

- **Thermal sensation log.** The inclusion of the thermal sensation log sheet proved to be useful in understanding general comfort preference and individual profiles of participants. Firstly, it provided evidence that participants were willing to complete them in their own time, this is particularly useful for planning future survey methodology. Secondly, the additional comfort temperature data allowed for more robust comparison with monitored indoor temperature. However, the lack of context provided by the thermal sensation log sheet is a limitation, no information is available of the clothing level, metabolic rate or occupancy time in the room, which can be addressed in the next survey run.

- **Comfort surveys.** While the increased number of comfort temperatures acquired per participant was useful, a total of four still leaves a great deal of room for error in determining actual comfort temperature. In some cases, it can be difficult to determine if contextual factors may be influencing results. This could be overcome by a greater number of comfort measurements.

- **Occupancy data.** The long term monitoring of indoor air temperature combined with the thermal comfort surveys provides a valuable database for analysis however a lack of occupancy data is a limitation. Due to the varied and unpredictable occupancy hours of many University students, only occupancy sensing instruments would provide this information however this is considered to be beyond the scope of this study.

3.5 App study

3.5.1 Study design

The method for the final phase of data collection differed from the previous studies in that assessment of thermal comfort was conducted using a custom built smartphone application. Indoor temperature and humidity were monitored in the same way as in the previous studies. The benefits of this approach are that it will be possible to acquire many more comfort votes with the inclusion of some contextual information such as clothing level and occupancy time in room. These contextual factors were a limitation of the thermal sensation log sheet as employed in the in-depth study. While air flow is usually considered crucial to assessment of thermal comfort, the low values recorded to date in Mayflower halls mean that it was deemed negligible. Initial installation of the data loggers was accompanied by a face-to-face questionnaire which included personal details and participants' backgrounds, as with the previous studies. This method aimed to acquire a similar number of responses per participant therefore increasing reliability compared to the logsheet where the number of responses differed greatly.

Participants were asked to complete the 10 question survey once a week for the duration of the occupancy (excluding vacation and exam periods). Figure 3.9 shows a selection of screeshots of the survey app. This approach had the potential to achieve over 1000 comfort votes, though this is subject to continued cooperation of participants over an extended period of time, assuming similar participation rates as the in-depth study. The study was approved by the Faculty ethics committee and selected supporting documents are included in Appendices B and C. This includes the survey questions (face to face and app), participant information sheet and consent form.

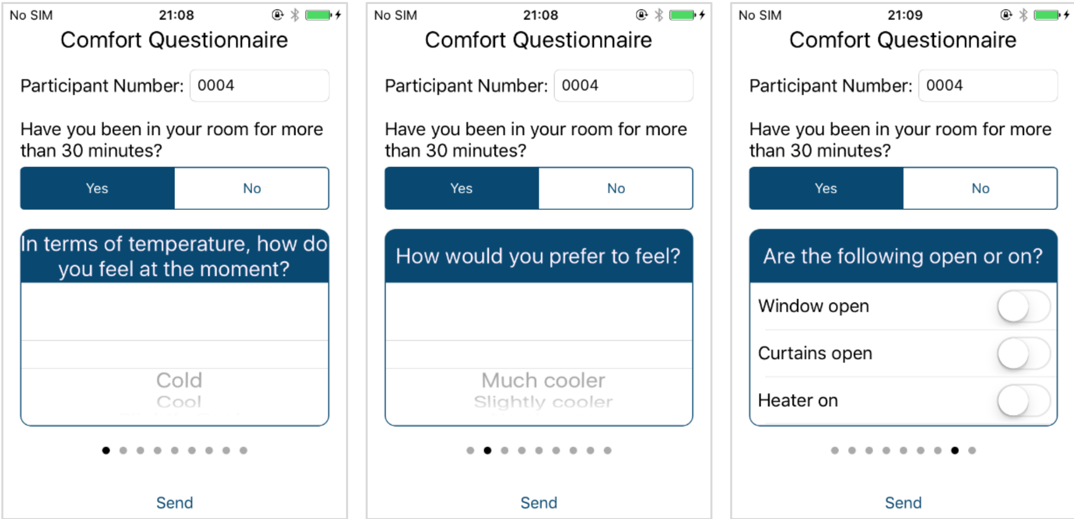


Figure 3.9 Sample screenshots of the comfort survey app

3.5.2 Sampling & Recruitment

The sampling frame for the app based study was all first time residents of Mayflower halls commencing in the academic year 2016-2017. Due to the reduced time commitment resulting from a fewer number of face-to-face surveys, the maximum number of participants was not limited and was dependent on the number of volunteers. Again, priority was given to volunteers arriving at Mayflower from different climate zones. In an effort to promote engagement, incentives were offered based on the number of complete survey responses sent:

- £15 Amazon voucher for all participants who complete 1 survey per week for the duration of the study
- £20 Amazon voucher for all participants who complete more than 1 survey per week in at least 50% of the duration of the study
- £25 Amazon voucher for the top 5 respondents

3.5.3 Review

The remote submissions of comfort surveys using the app successfully enabled a high number of responses per participant with reduced time commitment from the researcher. However, there was a higher dropout rate in this study compared to the face-to-face study with 44% of the initial participants having dropped out by non-response by the end of the study period. This may be due to the lack of personal engagement resulting from fewer visits from the researcher. However, the personal profiles that were obtained provided valuable information about individuals behaviour and preferences over a longer period of time.

3.6 Instruments

3.6.1 Thermal comfort sensing station

The ISO 7726 (2001b) compliant DeltaOhm HD32.3 device was used for measuring indoor environmental parameters during the thermal comfort surveys. The sensing station, pictured below, consists of a globe thermometer, combined air temperature and relative humidity probe and omnidirectional hot wire probe. ISO 7726 (2001b) recommends that sensors be placed 1.1m above floor level (for seated participants). Due to practical limitations given the number of surveys conducted, it was not possible to measure this in each room therefore the probes were placed at approximately head height. The technical specifications of each probe in the device are given in Table 3.1.

Table 3.1 DeltaOhm HD32.3 technical specifications

Parameter	**Specification**
Globe thermometer	
Range	-10^{o}C to +100^{o}C
Resolution	0.1^{o}C
Accuracy	1/3 DIN (±0.1 at 20^{o}C)
Omnidirectional hot wire probe	
Range	0.1 m/s to 5 m/s
Accuracy at 0-1 m/s	0.2 m/s
Accuracy at 1-5 m/s	0.3 m/s
Combined temperature and relative humidity probe	
Temperature range	-40^{o}C to 100^{o}C
Humidity range	0% to 100%
Temperature accuracy	1/3 DIN (±0.1 at 20^{o}C)
Humidity accuracy at 0%-90%	± 1.5% RH
Humidity accuracy at 90%-100%	±2% RH

Figure 3.10 Image of MadgeTech RHTemp101A temperature and relative humidity data logger (left) and DeltaOhm HD32.3 environmental measurement kit (right) for air temperature, globe temperature, relative humidity and air velocity

3.6.2 Indoor environmental monitoring

MadgeTech RHTemp101A devices were used for long term monitoring of indoor air temperature and relative humidity. Devices were positioned either above the wardrobe or attached to the side of the bookcase ensuring that they were away from the heater, would not receive direct solar radiation or cause disturbance to the occupants. The ISO compliant device specifications are shown in Table 3.2.

Table 3.2 MadgeTech RHTemp101A technical specifications

Parameter	Specification
Temperature	
Range	-40°C to +80°C
Resolution	0.01°C
Accuracy	± 0.5°C
Humidity	
Range	0% to 95%
Resolution	0.1%
Accuracy	± 3% RH
Reading rate	1 per second to 1 per 24hr
Memory	1,000,000 per channel

The indoor air temperature sensors were tested against the sensing station to check for accuracy and correlation. Twenty seven temperature sensors were placed inside a box and next to the sensing station at desk height in an office which experiences significant temperature changes due to low levels of insulation. All the sensors were placed in a location that would not receive direct solar radiation. Figure 3.11 shows the results of the test period which covers most of the experimental temperature range. The Delta Ohm device responds faster to changes in conditions due to the fact that the small MadgeTech devices were placed inside a box for testing. It is observed that the measurements of air temperature lie within the accuracy level of the measurement devices. Furthermore, the MadgeTech air temperature devices record values close to the globe temperature than air temperature which is likely to be due to it being encased in a small black box as shown in Figure 3.10. This means that the air temperatures from the dataloggers are reliable enough to be used for comfort temperature calculations instead of globe temperatures.

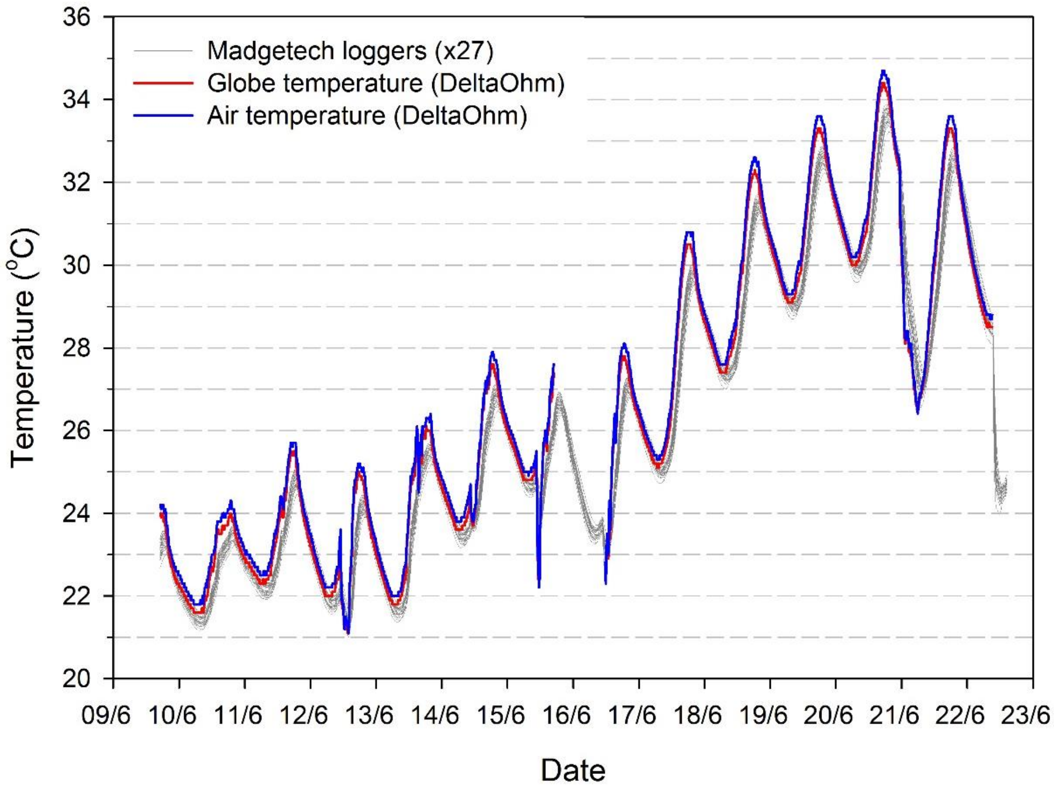


Figure 3.11 Comparison of MadgeTech RHTemp101A temperature loggers and DeltaOhm HD32.3 globe and air temperature sensors

3.7 Energy Modelling

The data acquired during the field studies were used to inform a TRNSYS simulation to estimate the variation in heating demand resulting from occupants' mixed thermal preferences. This section outlines the software used, model inputs and assumptions.

3.7.1 TRNSYS simulation software

A number of tools are available for the assessment of energy consumption in buildings (Foucquier et al. 2013; Crawley et al. 2008). These tools are typically one of three types of thermal model: multizone, zonal or computational fluid dynamics (CFD). All three types of model are valuable for different applications as Foucquier et al. (2013) outline in their review paper. Multizone or nodal thermal models are typically straightforward to implement with comparatively low computation time and are applicable for determining energy consumption (heating or cooling load) and average indoor temperature (Foucquier et al. 2013). Therefore, this study employs a multizone thermal model in the form of TRNSYS (Klein 2017).

TRNSYS is an accredited transient simulation software developed by the Solar Energy Laboratory, University of Wisconsin- Madison. The open, modular structure has made TRNSYS a successful tool for a number of applications including renewable energy systems and low energy buildings (Lomas et al. 1997). A building simulation TRNSYS project consists of a visual interface, TRNSYS Simulation Studio, where components can be added and connected to set the simulation parameters (Crawley et al. 2008). Components are known as 'types' for example a multizone building is referred to as 'Type 56'. The Type 56 component is edited using the TRNBUILD GUI program or by editing the text file directly.

3.7.2 TRNSYS model outline

The simple shoebox model used to estimate the energy use for heating by individual occupants is summarised in Figure 3.12. The room model, edited in the TRNBUILD program, requires basic characterics such as floor area, zone height, window area and orientation. This is then provided a further input of occupancy profile with linked internal gains (lighting and computing). Finally, in order to account for the shading imposed by the three buildings of the complex, an inbuilt component (Type 67) was used to modify the solar irradiation from the weather file. These inputs are discussed further in the following section.

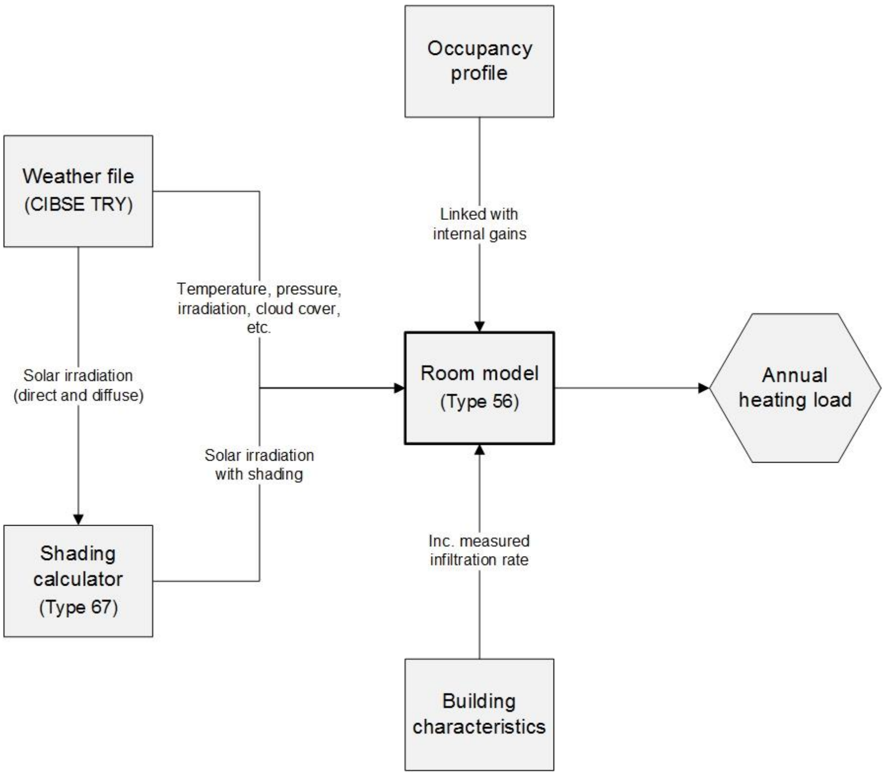


Figure 3.12 TRNSYS model outline for annual heating load estimation at Mayflower halls of residence

3.7.3 TRNSYS model inputs

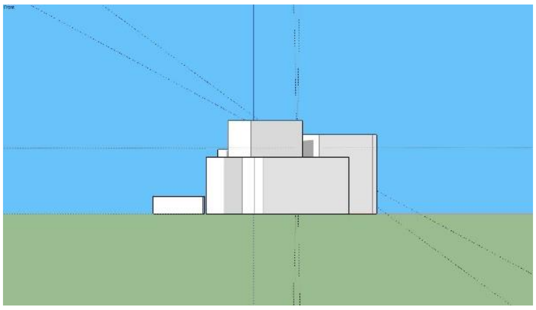
Weather Files

Weather files for the simulation were purchased from the Chartered Institute of Building Service Engineers (CIBSE) who provide the industry standard weather files for building performance. The CIBSE weather files use measured weather data from across the UK taken from the UK Meteorological Office to produce two types of weather file: test reference year (TRY) and design summer year (DSY). The TRY selects 12 separate months of weather data from a 30-year baseline (1984-2013) based on being the 'most average' month in the set in terms of air temperature, relative humidity and cloud cover (as a proxy for solar irradiation) (Virk & Eames 2007). These parameters are used to select the three months from the baseline with the lowest ranking. The representative month for that location is then selected based on the most average wind speed (Virk & Eames 2007). This methodology is based on the ISO standard (BSI 2005). The DSY weather files represent warmer than average years and are used to assess overheating risk in buildings. These also use a 30-year baseline to produce 3 probabilistic weather files representing different types of warm summer events. The method used for selection is based on the CIBSE TM49 (CIBSE 2014).

Shading

The location and layout of the Mayflower halls complex (Figure 3.1 and Figure 3.4) means that solar shading resulting from nearby buildings must be accounted for in the simulation. This was done using the TRNSYS Type 67 component which reads a text file containing the angular heights of the obstructions at regular intervals. In this case, a 22.5 degree angle on the horizontal was selected to provide suitable accuracy for the shading obstructions based on comparison with a higher resolution option (11.25 degrees). Based on the position of the sun in the sky (calculated from the weather file), TRNSYS then produces either a 0 or 1 depending on whether the beam radiation is blocked or visible (Solar Energy Laboratory 2009). It also outputs a value between 0 and 1 representing the percentage of the diffuse radiation that is visible (Solar Energy Laboratory 2009).

The angular heights of the obstructions were estimated using SketchUp as shown in Figure 3.13. Each façade of Block A and B was divided into 3 height zones; low, middle and high to account for different levels of shading. Due to its lower overall height, Block C was divided into two levels. The 22.5 degree intervals were marked out on the horizontal plane half way up the height zone (low, middle or high) and the obstruction distance and height was measured for each point. This was repeated for each orientation and each height zone to provide the full input for the Type 67 shading mask.



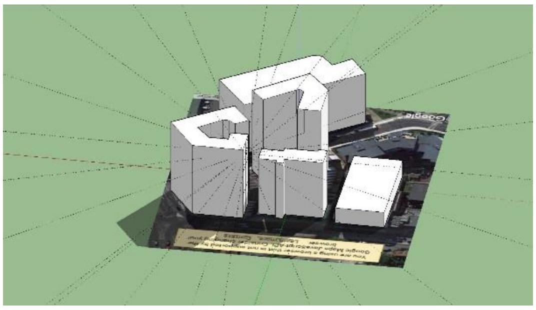


Figure 3.13 Sketch up screenshot showing the method for estimating angular heights of obstruction for each facade of Mayflower halls complex

Building characteristics and occupancy

The building characteristics required for the simulation are summarised in Table 3.3 alongside the sources of these values. The window and wall U-values were taken from the design Energy Performance Certificate (EPC) and the room area and height were measured using a laser distance meter. The internal gains for the model were linked in to the occupancy such that the lighting (5 W/m^2 over 4m^2) and computing (80 W) are assumed when the room is occupied and off between the hours of 00:00 and 08:00. These inputs are summarised in Table 3.3.

Table 3.3 Mayflower halls building characteristic inputs for TRNSYS simulation

Parameter	Value	Source
Window U value	1.4 W/m^{2}K	EPC certificate
Wall U value (external)	0.34 W/m^{2}K	EPC certificate
Room floor area	13.6 m^2	measured
Room height	2.34 m^2	measured
Window area	1.13 m^2	measured
Internal gains		
Lighting	5 W/m^2 for 4m^2	estimated
Computing	80W	estimated

Determination of infiltration and ventilation rate using a tracer gas

A multipoint decay method, as described by Laussmann and Helm (2011), was used to determine the infiltration rate of a typical ensuite room in Mayflower Halls. Carbon dioxide (CO_2) was used as the tracer gas due to its simplicity and the availability of sensors for concentration measurements. One CO_2 measurement device (Extech SD800) was placed outside the window to measure the background CO_2 concentration and one was placed in the centre of the room. Both sensors recorded the CO_2 concentration at one minute intervals. With the windows closed, the CO_2 level was increased by reacting bicarbonate of soda with lemon juice; a fan was used to circulate the air and ensure an even distribution of CO_2. When the CO_2 level reached 1500 ppm, the window was set to the test conditions and the room was left unoccupied with the CO_2 concentration monitored remotely until the concentration dropped below 800 ppm. The test was conducted under 2 different conditions: window open and window closed.

The window open test provides the infiltration rate and the window open test represents the infiltration and ventilation rate together. This is in order to determine a maximum and minimum possible ventilation rate. In reality, it is likely that occupant's would experience a ventilation rate in betwteen these values at certain times of the day as their curtains would be closed which would limit the air flow. Figure 3.14 shows the decay curves with the window open (top) and closed (bottom).

Calculation of ventilation rate, in air changes per hour, followed the guidelines set out in ISO 12569 (ISO 2012) and is given by the equation (Calver et al. 2005; Laussmann & Helm 2011):

$$N = [\ln\left({C_{int}}^{t0} - C_{ext}\right) - \ln({C_{int}}^{t1} - C_{ext)}]/(t^1 - t^o)$$

Where C_{int} is internal CO_2 concentration, C_{ext} is external CO_2 concentration, $t^o$is the start time and t^1 is the end time.

Use of this method requires that the ventilation rate is constant. This was determined by confirming a linear relationship between $\ln C(t)$ and t. In practice, since the concentration level is recorded at intervals, linear regression analysis is used with the slope giving the air changes per hour (Calver et al. 2005) as shown in Figure 3.14.

Any tests in which the natural logarithm of the difference between internal and external CO_2 differed significantly from the others, as determined by ANOVA analysis, were not included in the calculation to determine the mean air change per hour for each setting. This included Tests 11 and 12 in the window open state and Test 9 in the closed state. The final infiltration rates are shown in Table 3.4.

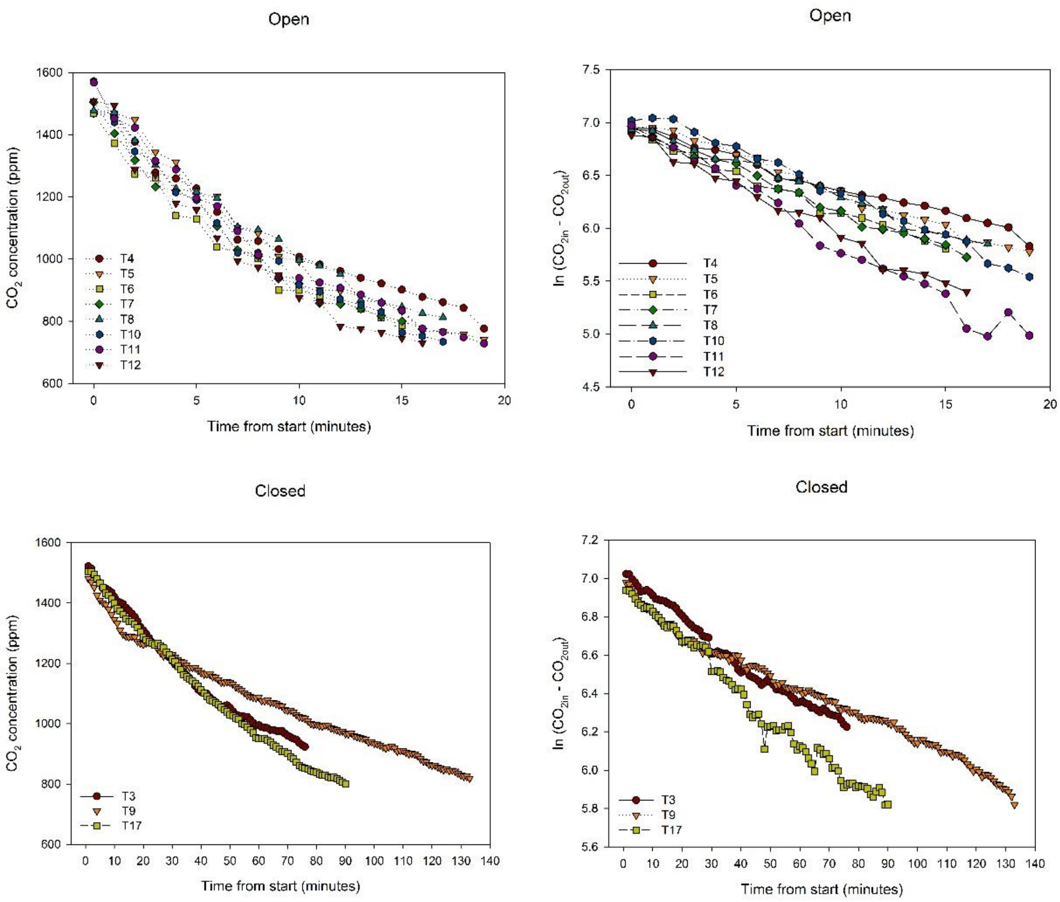


Figure 3.14 Left: CO_2 decay curves with window open (top left) and closed (bottom left). Natural logarithm of the difference between outdoor and indoor CO_2 concentration with the window open (top right) and closed (bottom right); the slope of these points gives the air changes per hour.

Table 3.4 Summary of Mayflower halls infiltration test results determined using multipoint CO_2 decay test

Test condition	**ACH (/hr)**	**Error (/hr)**
Window open	4.2	0.3
Window closed	0.7	0.1

3.8 Ethical considerations

All research activities involving participants are required to conform to the University Ethics Policy (University of Southampton 2016). No research activities were conducted until approval had been granted from the Faculty of Engineering & the Environment Ethics Committee. This work is covered under the following ethics application identification numbers: 13832, 14799, 18221 and 23863.

Since this research involved human participants, the fulfilment of a number of criteria was required to ensure compliance with the University Ethics Policy. These requirements are outlined below:

- **Informed consent.** In both the pilot study and in depth study, first contact was made by email which included a brief description of the purpose of the study and the requirements of participants should they choose to participate. Furthermore, the in-depth study email invited occupants to meet the researcher to find out more information before volunteering for the study should they wish to. Since the planned surveys are required to take place in the occupants' private bedrooms, this could help to alleviate any reservations. Participants who opted in to the study signed a consent form at the start of the first survey visit. The consent form indicated highlighted that the study is part of a research project and that all data may be used for that purpose and that all data would be handled in accordance with the Data Protection Act (Appendix C - II).

- **Withdraw process.** Withdrawal from the study was by email. This was specified in the consent form signed by participants at the start of the first survey. A leaflet containing the researchers email was also left with all participants at the first survey visit.

- **Confidentiality.** All personal information provided is coded such that only the researcher is able to trace the data back to a single participant. The Doodle Poll used to schedule surveys was anonymised such that only the researcher was able to see the name and selected time slot of each participant.

- **Data protection.** All data provided is treated in accordance with the Data Protection Act 1998 (Crown Copyright 1998). This requires that:
  - Only the necessary and relevant personal data be collected
  - All data collected only be used for the intended purpose in this research study
  - All data be stored on password protected computers or in locked drawers to minimise risk of accidental loss, damage or unauthorised disclosure.

- **Risk assessment.** This research study poses low risk to both the researcher and participants. To ensure that risk remained at a minimum, the following protocol was adhered to:
  - Contact was made with supervisors at the start and end of each survey day
  - In accordance with Mayflower building management, the researcher signed in and out of the complex each day. Furthermore, Mayflower Halls employs 24 hours security should any issues arise.

3.9 Outline of study design

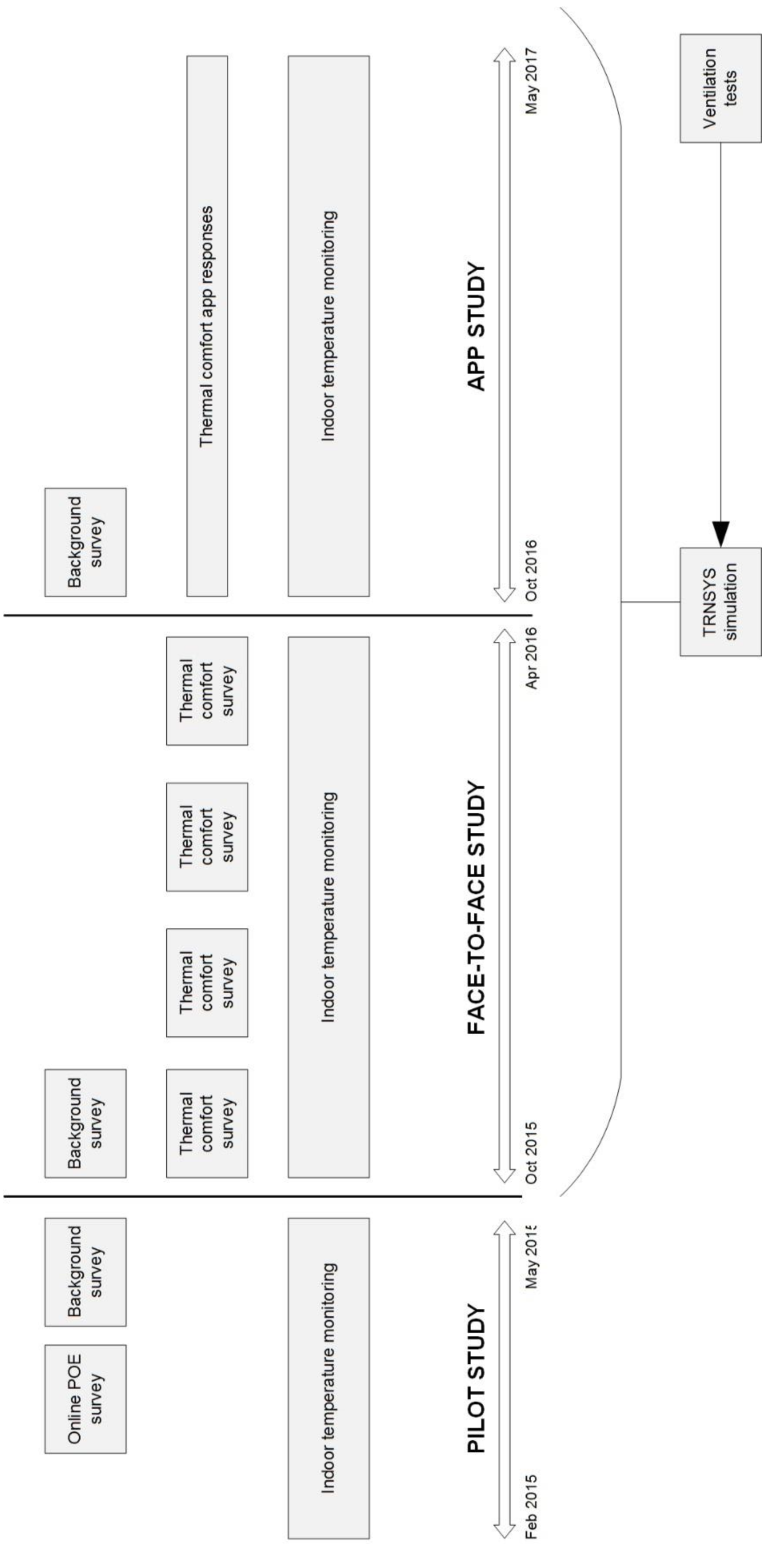


Figure 3.15 Summary of study design

Chapter 4

Results & Discussion: Pilot study

This section outlines the analysis carried on the data collected during the pilot study which aims to test the hypothesis that there are differences in the thermal preferences of occupants previously living in different climates. Many of the results presented here can be found in a paper published in Energy and Buildings (Amin, Teli, James, et al. 2016); a full manuscript is provided in Appendix A - I.

4.1 Overview of Occupants

Of the 223 respondents to the online survey, 123 (55%) were female, 96 (43%) were male and 4 (2%) didn't state. The age of respondents ranged from 18 to 52 with 139 (62%) being 18-19, 61 (27%) being 20- 24 and 21 (9%) being 25 or over; 2 respondents' (1%) ages are not stated. Participants were asked which city they had mostly been living in for the two years prior to moving into the case study building. These responses were then grouped into "cool/cold" (Category A) or "warm/hot" (Category B) based on whether the average winter temperature was as cold as or colder than the UK. The classification considered winter temperature since the study was conducted during the heating season. Overall, there were significantly more responses from Category A climates (174) than Category B climates (46), and 3 participants did not state the location of their previous residence. Figure 4.1 shows the location of previous residence of all online post occupancy survey respondents.

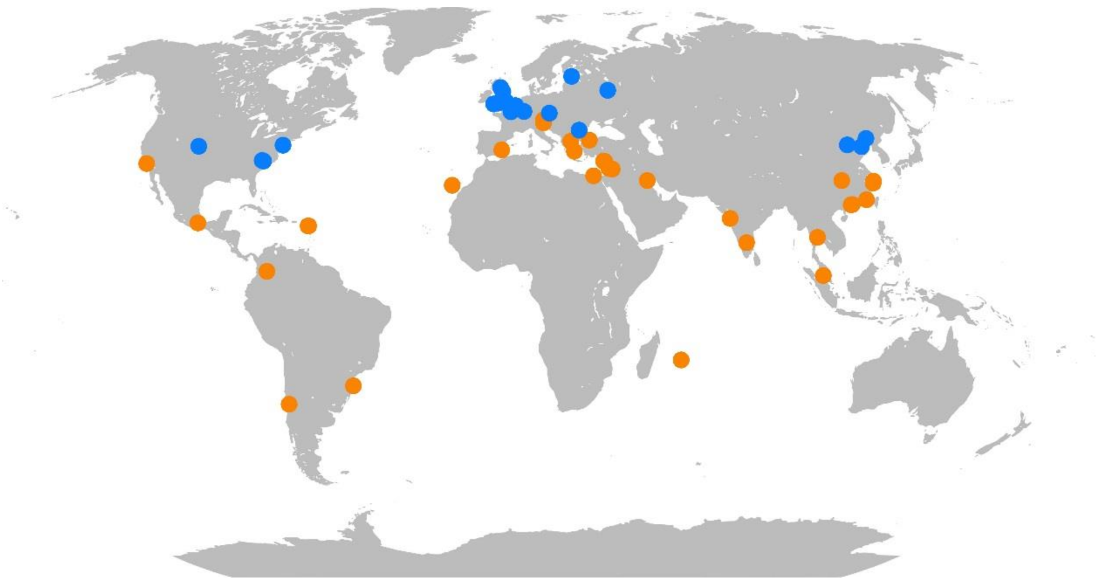


Figure 4.1 World map showing the previous location of residence for online post occupancy evaluation survey. Category A climates (cold/cool) shown in blue and Category B climates (warm/hot) shown in orange.

The number of hours reportedly spent in the bedroom (i.e. their private space) including sleeping time on a typical weekday and typical weekend day are shown in Figure 4.2. This indicates a highly irregular occupancy profile distribution in comparison to office buildings or households with some respondents reporting spending less than 5 hours in their bedroom and others reporting 23 hours; this represents a standard deviation (σ) of 3.1. It is likely that some of the responses that indicated a very low number of occupancy hours were due to a misunderstanding of the question on the part of the participants such that sleeping time was not included in their response despite the question stating that it should be. Greater variation in number of hours spent in the bedroom is evident on a typical weekend day with responses varying from 0 to 24 and a standard deviation (σ) of 4.6. Observing such variation in number of occupancy hours indicates clearly how challenging this type of building is where it would be unrealistic to hold it to any of the existing occupancy profiles for residential buildings where occupancy hours are taken to be in the region of 13 hours for a working couple or 20 hours for a retired couple (Martinaitis et al. 2015) as shown in Figure 4.2. This in part may be due to the mixed use of such buildings where bedrooms serve also as study and social spaces and where students' lecture schedules vary greatly especially between degree programs.

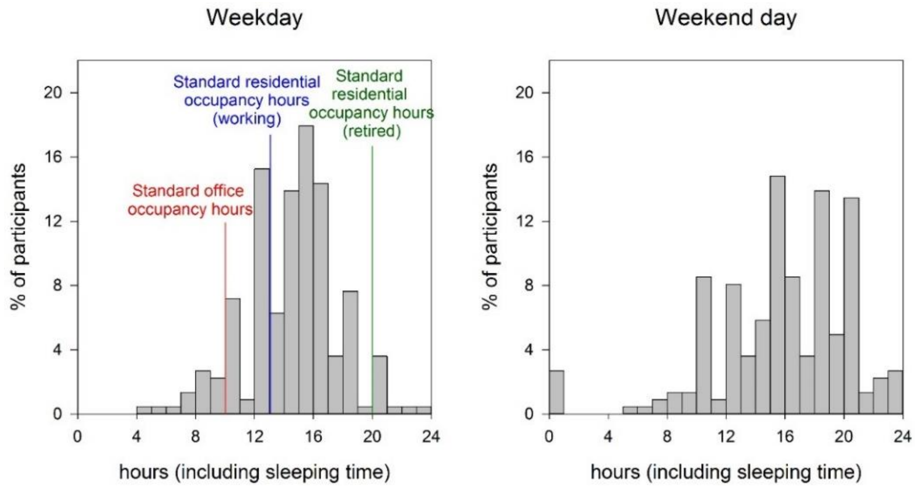
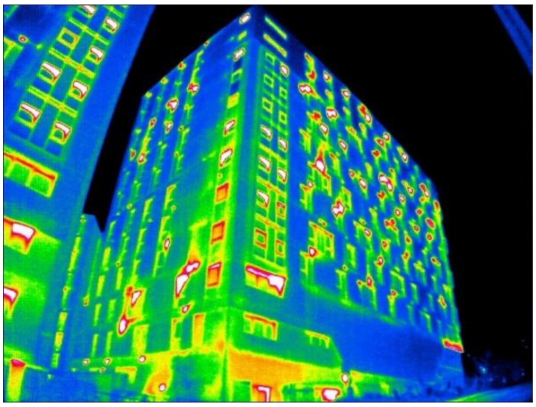


Figure 4.2 Histogram showing reported number of hours spent in the bedroom (including sleeping time) by residents of Mayflower halls of residence complex during a typical weekday (left) and weekend (right) day. Also shown are some benchmark values for number of occupancy hours (CIBSE 1998) for office buildings (red) and for two typical residential scenarios, working (blue) and retired occupants (green) (Martinaitis et al. 2015)

4.2 Use of Indoor Environmental Controls

Responses to questions on the frequency of use of indoor environmental controls, specifically the use of heater, window opening and use of curtains show diversity in the behaviour of occupants. Use of the heater shows a relatively even spread across the categories with a majority reporting using the heating controls less than once per month ("never"); this does not, however, specify the setting the heater is left at for most of the time. Respondents demonstrated a high rate of window opening and curtain use with 76% and 77% respectively reporting using these controls either daily ("often") or more than once a day ("frequently"). As with use of heating controls, it is not specified whether those reporting opening windows or curtains less than once per month have these controls open or closed for the majority of the time. However, infra-red imaging indicates that a significant percentage of windows are in the open state during the heating season as highlighted in Figure 4.3 and Figure 4.4. The infra-red images were taken before sunrise to eliminate the influence of solar radiation on the results. The ambient temperature at the time the image was taken was 5^{o}C.



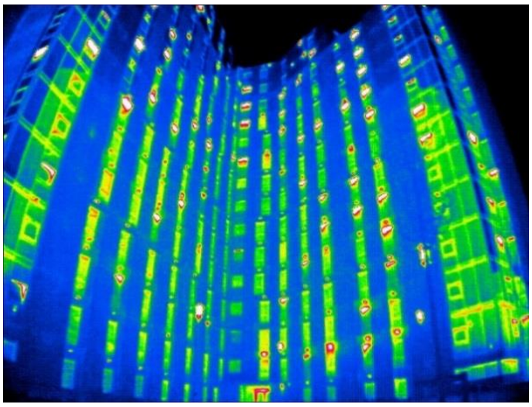


Figure 4.3 Infra-red image of Mayflower Halls Block A south east facade

Figure 4.4 Infra-red image of Mayflower Halls Block B internal east and north west facades

When the use of controls are considered by gender, male participants reported using both windows and curtains more than once a day ("frequently") more than female respondents. In the case of curtain use, this was 47% for males and 33% for females and for windows, 50% for males and 37% for females. In both cases, females have a higher representation for the next category representing use of these controls daily ("often"). By contrast, male respondents report using their heating controls less than once per month ("never") more than female respondents (40% and 25% respectively) with female respondents carrying a higher percentage in categories representing more frequent use of heating controls. However, these differences, shown in Figure 4.5, are not significant as indicated by the Chi-squared test p-values > 0.5 and could imply that factors other than gender play a more significant role in determining behaviour with respect to indoor environmental controls e.g. familiarity with type of heating system or control regime in previous residence.

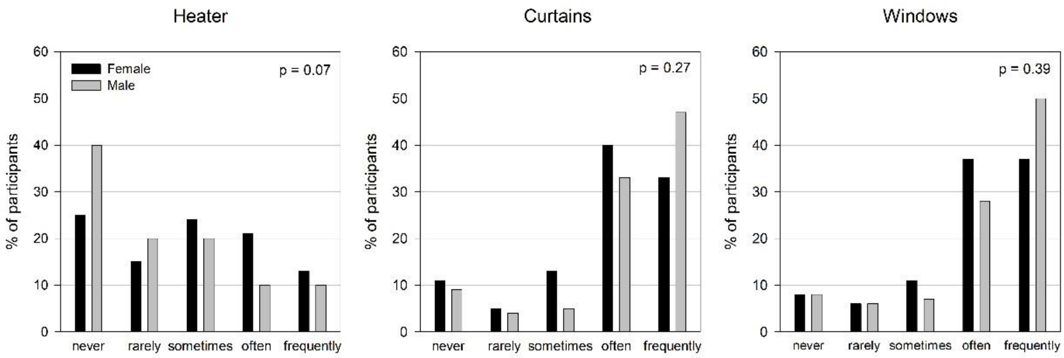


Figure 4.5 Occupants' reported use of indoor environmental controls for heating, window opening and curtains classified by gender where "never" is less than once per month, "rarely" is once per week, "sometimes" is 1-2 times per week, "often" is daily and "frequently" is more than once per day. The difference between Male and Female is not significant, as indicated by the p-values > 0.5.

Finally, the use of controls were examined with respect to participants' previously experienced climate. It is observed that those from Category A (cool, cold) climates report higher use of curtains and windows with higher percentages reporting 'frequently' and lower use of heating controls ('rarely' and 'never'). Chi-squared test were conducted to test if these differences are significant; while the p-values for curtain use and window use are smaller than 0.5, the small expected values mean that this may be incorrect and should be considered with caution.

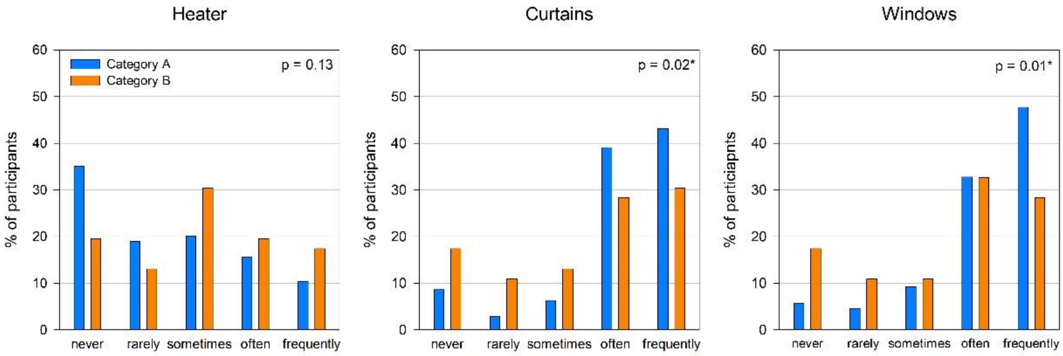


*Figure 4.6 Occupants' reported use of indoor environmental controls for heating, window opening and curtains classified by climate prior to moving to the case study building where "never" is less than once per month, "rarely" is once per week, "sometimes" is 1-2 times per week, "often" is daily and "frequently" is more than once per day. Category A refers to "cool/cold" climates and Category B to "warm/hot" climates. P-values are shown for the Chi-squared tests where * indicates that the results should be considered with caution due to the small expected values.*

To understand how use of indoor environmental controls affects overall satisfaction with the indoor environment, the use of controls is shown along with responses regarding how occupants describe the temperature in their rooms during the winter. The majority (56%) of the residents feel that the temperature is satisfactory or 'ok' and there are more residents reported being 'too warm' (8%) than 'too cold' (2%). Responses indicating slightly 'too warm' or 'too cold' are similar in number at 18% and 15% respectively. Considering heater use, it is interesting to note that those who report being satisfied with the indoor temperature in their bedroom are the dominant group across all categories of heater use. This implies the importance of end user control of the indoor environment to achieve satisfaction and comfort. Furthermore, those that report feeling 'too warm' or 'a bit too warm' are strongly represented in the category of 'never' using the heater and 'frequently' using the windows. This implies adaptive comfort behaviours despite residents not being entirely satisfied with the resulting temperature conditions. However, it is unclear at this stage whether or not these adaptations can be said to be effective since the circumstances under which each type of action is taken is not stated.

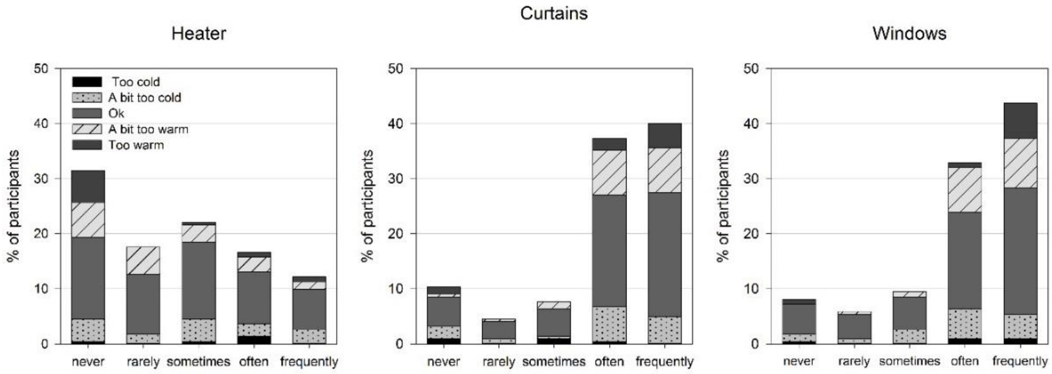


Figure 4.7 Stacked bar chart showing occupant's reported use of indoor environmental controls categorised by occupants' general description of indoor temperature during the winter (223 respondents)

4.3 Indoor environment monitoring

Monitored data of temperature and relative humidity at 5 minute intervals was collected from December 2014 to May 2015 in 30 rooms of Mayflower Halls alongside the same questionnaire used in relation to use of indoor environmental controls. The results showed average indoor temperatures varying from 19°C to 32°C, with minimum and maximum temperatures reaching 12.4°C and 32.9°C respectively. Since a certain degree of variation is expected over the year due to seasonal weather changes, a shorter period of time, the month of February 2015, was considered. This month was selected as it is during the heating season and academic term time so the student residents would be occupying the buildings. The mean ambient temperature for this period was 4.1°C in the South of England which is 0.4°C lower than the long range (1981-2010) average for this month (Met Office 2015).

Figure 4.8 shows the air temperature distribution of these 30 rooms for February 2015 where the box plots represent the 10th, 25th, 75th 90th percentiles and median, the red line represents the mean and the outliers are shown by the grey circles. It can be seen that while the majority of the samples presented here have mean values that lie within the recommended indoor temperature range for heating, taken from EN 15251 (CEN 2007), they all have values outside this range as depicted by the grey dots. This has implications for the design process since it is likely that mean values of indoor temperature are used in energy models. It is evident that these may not lead to acceptable indoor temperatures at all times which could lead to negative feedback at the POE stage, depending on frequency of occurrence. Interestingly, as seen in Figure 4.7, students' general feedback on their room's temperature is positive, which means that the range of room temperatures for this diverse population is acceptable overall. This is perhaps a reflection of the 'bundled' charging mechanism for rent and heating resulting in residents being able to use windows or heating controls without any personal financial penalty.

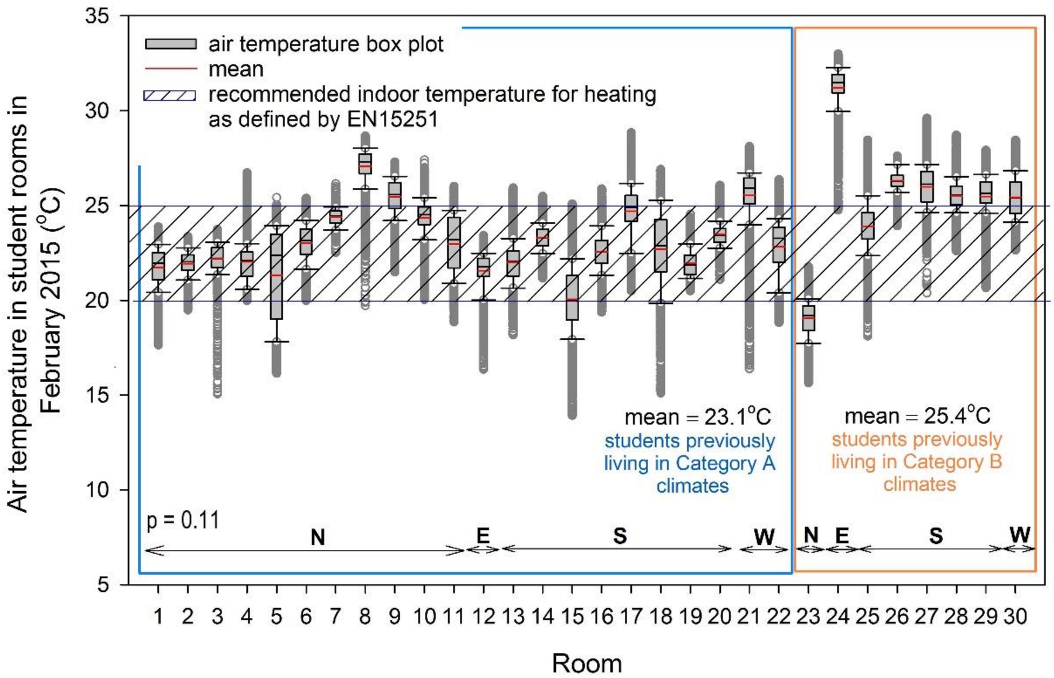


Figure 4.8 Boxplot of air temperature in 30 monitored rooms of Mayflower Halls of residence for February 2015 where the 10th, 25th, 75th, 90th percentiles and median are shown in the boxplot. The red line represents the mean and outliers (below 10th or above 90th percentile) are shown as the grey circles; students previously living in Category A (cool/cold) climates are shown in the blue box and Category B (warm/hot) climates are shown in the orange box. The rooms are grouped by facade orientation: North (N), South (S), East (E) and West (W) shown by the arrows. The shaded area represents the recommended indoor temperature for energy calculations taken from EN 15251:2007 (CEN 2007)

Also highlighted in Figure 4.8 are the participants in the sample who, for the two years prior to moving to the case study building, have been living in Category A (cool/cold climates) and those who have been living in Category B (warm/hot) climates, as described previously. It can be seen that the mean air temperature between the two groups differs by over 2°C where those from Category B climates have a mean of 25.4°C compared to 23.1°C for those previously living in Category A climates. One-way ANOVA did not find this difference to be statistically significant ($p= 0.11$). However, this difference is substantial considering in the climate of Southern England, where the case study is situated, since the typical ambient temperature during the heating season is 10°C compared to the typical heating set point of 21°C, meaning that a 1°C temperature difference can represent approximately 10% of the annual space heating load. It is also observed that 7 of the 8 (88%) participants from Category B climates had mean indoor temperatures outside the recommended range for heating, compared to 14% of the participants from Category A climates.

Considering also the orientations of the rooms, which could be influencing the indoor air temperature, it was found that in the Category A group, the average temperature for February 2015 for north facing rooms was 23.3°C compared to 22.6°C in South facing rooms. For the purpose of this study, north facing rooms include north-west and north-east and south facing rooms include south-west and south-east as north-south orientation will have the most significance during the winter. If room orientation was strongly influencing indoor room temperature we would expect that the south facing rooms would have a significantly higher temperature than the north facing. Instead, we see the north facing rooms exhibiting a higher temperature, though the difference cannot be said to be significant. This implies that room orientation may not be the most influential factor in determining room temperature during the heating season where it is likely that all rooms will require additional heating to maintain a comfortable temperature. However, further research is needed to confirm this as the sample size employed here is small.

4.4 Occupant perception of indoor environment

The participants were also asked to rank their overall perception of the temperature conditions in their bedroom during the winter where the response options were: Too cold (-2), A bit too cold (-1), Ok (0), A bit too warm (1) or Too warm (2). It is interesting to note that the average for the participants from Category A climates was 0.2, indicating that on average, these residents feel slightly warm at an average air temperature of 23.1°C. By comparison, Category B participants have an average perception vote of -0.4 indicating that they feel slightly cool at higher average air temperatures of 25.4°C. These responses are plotted against mean indoor temperature in Figure 4.9.

Considering then the cases where the mean indoor temperature value lies above the recommended range, it is interesting that only one participant (Room 27) answered "Too hot" when asked to describe the indoor temperature during the winter. Perhaps more notable however, is that 3 of the 6 Category B participants (Rooms 24, 28 and 29) whose mean temperature was above the recommended range all reported being either too cold or a bit too cold despite having average temperatures over 25°C with one (Room 24) having an extremely high average of 31°C. By contrast, the three participants from Category A climates whose mean values were above the recommended range all responded 'Ok' when asked about the temperature conditions in their rooms. This implies that while on paper, these indoor temperatures would be considered unacceptably high, in this instance, they are satisfactory for the occupant.

In Figure 4.9, an additional category, An, has been added to the data set which highlights the occupants from cool, non-UK climates in order to explore the effect of familiarity with cold conditions. This shows that there is only one resident from the UK whose living space is on average outside the recommended range. This could indicate that while some residents may be accustomed to similarly cold winters in their 'home' climates, a difference in temperature preference for their living space is leading to higher than recommended but comfortable mean indoor temperatures in a UK residence. Thus, it seems that the diversity in temperature preference may not be sufficiently well catered for given that many residents have expectations and adaptations that are significantly different than those accounted for in the relevant building standards. This will affect the building's energy performance thereby highlighting user driven performance gap in a halls of residence context.

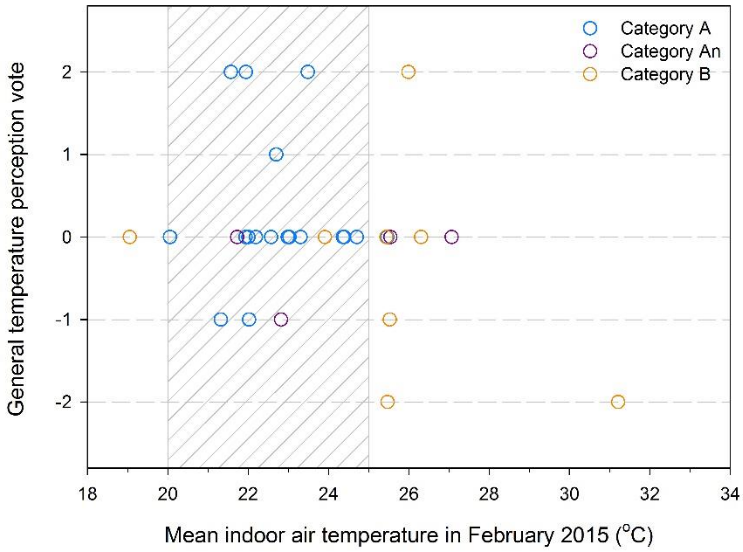


Figure 4.9 Plot of overall temperature perception vote for the winter against mean indoor temperature for February 2015 where -2 is Too cold, -1 is A bit too cold, 0 is ok, 1 is A bit too warm and 2 is Too warm on the y axis. The shaded area represents the recommended indoor temperature for energy calculations taken from EN 15251:2007 (CEN 2007)

4.5 Comfort temperatures

Comfort temperatures were calculated using the Griffiths method as outlined in Section 2.3 for each data point. The running mean temperature for the survey period ranged from 10.0°C to 11.7°C. The group means and standard deviations are provided in Table 4.1 and summarised in the box plot shown in Figure 4.10. If Categories A and An are considered together as they are in the assessment of monitored indoor temperature (Figure 4.8), the mean comfort temperature is 23.4°C compared to 24.2°C for Category B. These comfort temperatures reflect differences found in the monitored air temperatures, though one-way ANOVA tests revealed no significance in the difference between the three groups with a p-value of 0.06. This may be due to small and unequal sample sizes. Comparing the measured comfort temperatures to those calculated according the EN15251 standard, it is apparent that the majority of Category A responses lie within these limits. The same is not true for either of the other two groups where the median lies on the upper limit for Category An and above the upper limit for Category B. This, like the monitored air temperatures, provides evidence that designing for European standards may not be suitable for all residents.

Table 4.1 Summary table of comfort temperatures

Climate	N	Mean (°C)	σ
Category A	18	22.5	2.17
Category An	4	25.1	0.9
Category B	8	24.2	2.8

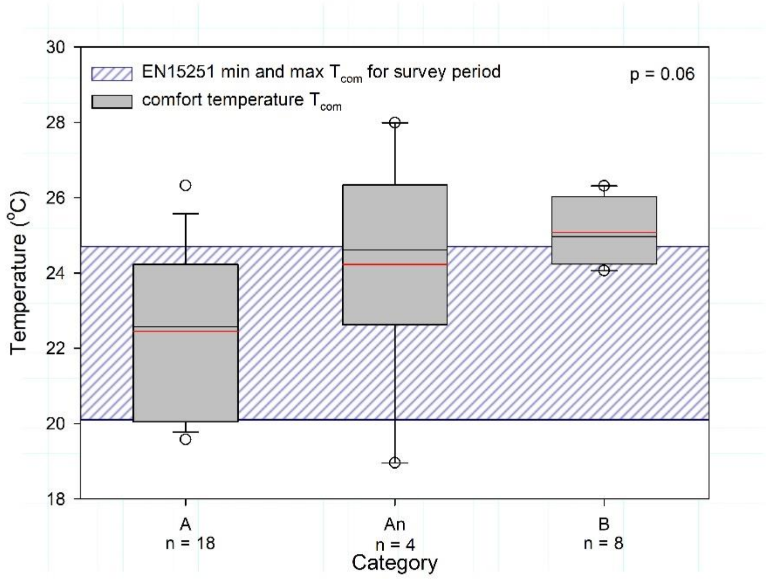


Figure 4.10 Comfort temperatures calculated using the Griffiths method grouped by climate of previous residence. The shaded area represents the upper and lower limits for comfort temperature calculated according to EN15251 (CEN 2007) *for the survey period. The p-value > 0.05 indicates that the difference between groups is not significant.*

4.6 Summary

Results from on an online POE study of a newly built halls of residence complex were used to test the hypothesis that there are differences in the perceptions of indoor environments based on occupants' previous residence. While it is likely that some variation is due to differences in the conditions in the rooms due to orientation and floor level, it is evident that there are other influencing factors at play. Some of these, such as the level of 'pro-activeness' in addressing thermal discomfort, which is largely a personality trait, are hard to address and very difficult to predict. However, differences observed in use of controls by occupants from Category B (warm) climates indicate that there are factors relating to long term thermal history, previous experience of indoor environments and perhaps cultural practices that are driving behaviour. While this initial study does not draw any generalisations, this type of parameter has the potential to be included, in some capacity in the design process either as an input at the design stage or as part of a post occupancy, 'Soft Landings' approach (BSRIA 2014).

The second part of this study used monitored air temperature measurements for February 2015 along with questionnaire results to investigate variation in indoor temperatures in 30 rooms of the case study building complex. Mean temperatures ranged from 19ºC to 32ºC with a standard deviation (σ) of 2.4. While indoor temperatures cannot be expected to be uniform throughout a building like this, where there are many influencing factors both in building design and occupant preferences, this large range is striking. The mean values of temperature are also noteworthy when considered with respect to the recommended heating temperature range (20ºC -25ºC), where it was found that almost all the mean values that lay above this range were of rooms where the occupant had, for the two years prior to living in the case study building, been living in a warm or hot climate. Furthermore, some of these occupants reported finding the temperature in their room was generally too cold (or a bit too cold). This difference in indoor temperature preference is even more evident when considering residents from cool non-UK climates (Category An). It is shown that all but one of the rooms that had a mean temperature outside the 20ºC -25ºC range belonged to residents who have previously not been living in the UK. Furthermore, in this study, room orientation did not appear to have a strong influence on room temperature. Similarly to the monitored temperatures, when comfort temperature were compared with values calculated according to the EN15251 European standard, residents from the UK corresponded much more closely than residents from either Category An or Category B.

The pilot study provided an indication that perceptions of the indoor environment may be linked to occupants' thermal history. The following chapters explores adaptation of international students to the UK in more detail using data collected from two subsequent monitoring and survey campaigns.

Chapter 5

Results & Discussion: Thermal preference and comfort in a new climate

This section presents the findings from a two season residential field study in Mayflower halls of residence. First, an overview of the study is presented including details of the study sample and diversity in occupants' perceptions of the indoor environment. Next, the data collected is used to try and understand this diversity in preference based on occupants' thermal history and cultural background. Finally, behavioural parameters including clothing insulation and use of indoor environmental controls are considered for their significance in occupant comfort.

Parts of these results are published in conference and journal papers (Amin, Teli & James 2016; Amin et al. 2017) which can be found in full in Appendix A. A full set of app study individual profiles can be found in Appendix D.

5.1 Study overview

5.1.1 Overview of Occupants

Data was collected in the case study building, Mayflower halls of residence, in two consecutive academic years, 2015 to 2016 and 2016 to 2017. Due to the short term rental contracts in University accommodation, the sample is different in each year. Table 5.1 summarises the sample in each of the field studies. The different number of comfort survey responses in Year 2 is a result of the data collection method used whereby participants were asked to submit at least one comfort survey per week (with some exceptions) using a mobile app but were not restricted in the number of submissions.

Table 5.1 Summary of sample from Mayflower halls for field studies conducted over two consecutive years

	Year 1	Year 2
Total sample size (N)	47	22
Male	18	6
Female	29	16
Comfort survey responses	188	996
Category A	17	7
Category An	18	9
Category B	12	6
Study period	Oct 2015 – Apr 2016	Oct 2016 – May 2017

Table 5.2 Definitions of climate category groupings

Category	Description
A	Mostly living in the south of the UK for the two years prior to moving to Mayflower
An	Mostly living in a climate with winters as cold as or colder than Southampton for the two years prior to moving to Mayflower
B	Mostly living in a climate with winters warmer than Southampton for the two years prior to moving to Mayflower

In the Year 1 (Y1) face-to-face study, participants were excluded if they failed to complete all four survey visits (9 participants) or if the air temperature monitoring device failed to record data (1 participant). In the Year 2 (Y2) app study, participants were excluded if they failed to submit at least one comfort response remotely per week (17 participants), excluding university vacation and exam periods, with some exceptions allowed. The higher dropout rate in the Y2 study may be due to the greater engagement required of participants compared to the four surveys in Y1. However, the high response rate from a smaller sample provides useful insight into individual profiles. Participants were grouped by climate of residence prior to living in Mayflower based on winter temperature, as described in Table 5.2. The number of participants in each climate group is also shown in Table 5.1. At the second, third and fourth survey of the face-to-face study, occupants were asked to report their typical number of occupancy hours on weekdays and weekends (including sleeping time), these are shown in Figure 5.1. Much like the findings of the pilot study, the number of occupancy hours varies across the sample.

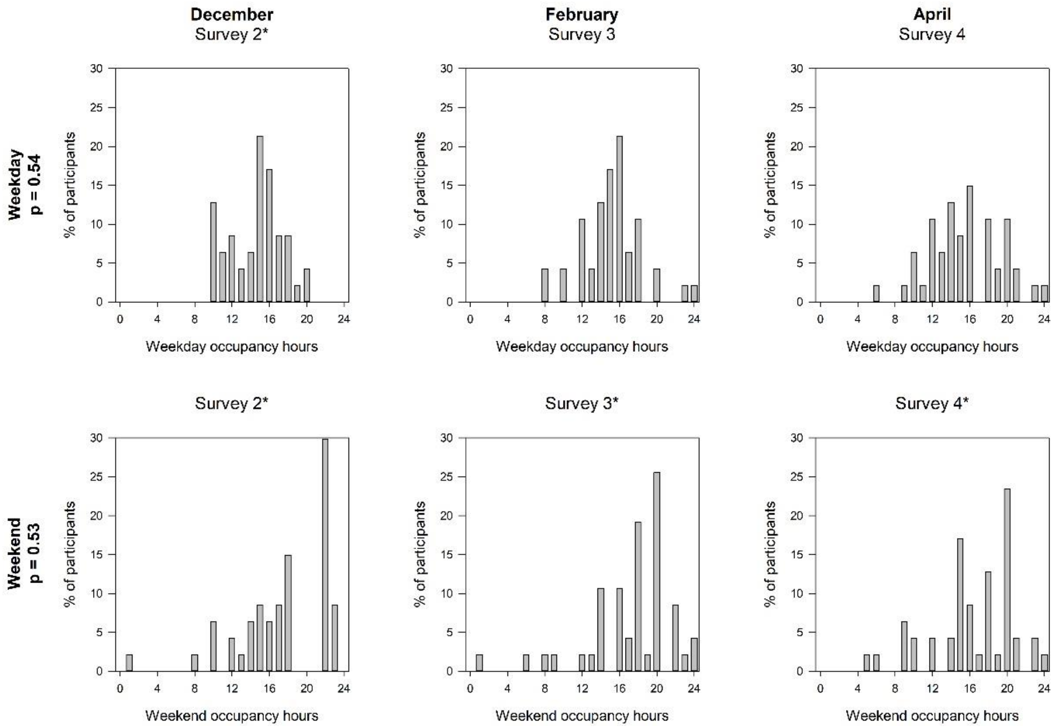
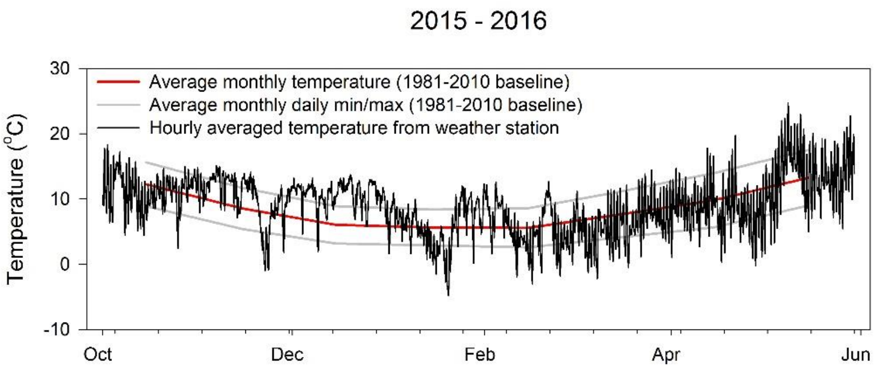


*Figure 5.1 Self-reported number of occupancy hours (including sleeping time) for weekdays (top row) and weekends (bottom row) from the second, third and fourth visit of the face-to-face study (n = 47). The p-values on the left-hand side indicate that there is no significant difference between surveys determined by Kruskal-Wallis one-way ANOVA and the * indicates where the data is not normally distributed determined by Shapiro-Wilk test (p > 0.05).*

5.1.2 Study period

Figure 5.2 shows the measured hourly outdoor temperature in Southampton taken from the IENGLAND121 weather station located in Southampton Docks (weatherunderground 2016), approximately 1.5 km from the case study site. Also shown is the monthly mean temperature (red) and monthly mean daily mean maximum and minimum temperature (grey) from a 1981 – 2010 baseline (Met Office n.d.). November 2015 was +2^{o}C warmer than average across the UK and conditions were particularly warm in southern England (Met Office 2016a). The 2015 – 2016 winter period (December – February) was the warmest since 1910 in England with December being the warmest since 1659 (Met Office 2016d). It was also the second wettest winter since 1910 with December seeing 2 to 4 times the average monthly rainfall (Met Office 2016d). The total heating degree days for the 2015-2016 winter period was 1532 (degreedays.net 2017), ~20% lower than the long term average of 1921 (CIBSE 2008). Spring 2016 temperatures averaged out to be close to the baseline with March and April slightly below average and May slightly above (Met Office 2016c).

Similar to the 2015 – 2016 winter, the 2016 – 2017 winter period was warmer than average with both December 2016 and February 2017 having mean temperatures warmer than the 1981 – 2010 average, +2^{o}C and +1.6^{o}C, respectively (Met Office 2017a; Met Office 2017b). The total heating degree days for the 2016-2017 winter period was 1747 (degreedays.net 2017), ~13% lower than the long term average of 1921 (CIBSE 2008). The spring of 2017 was warmer than average with March, April and May recording average temperatures +1.8°C, +0.6°C and +1.7°C above the baseline, respectively.



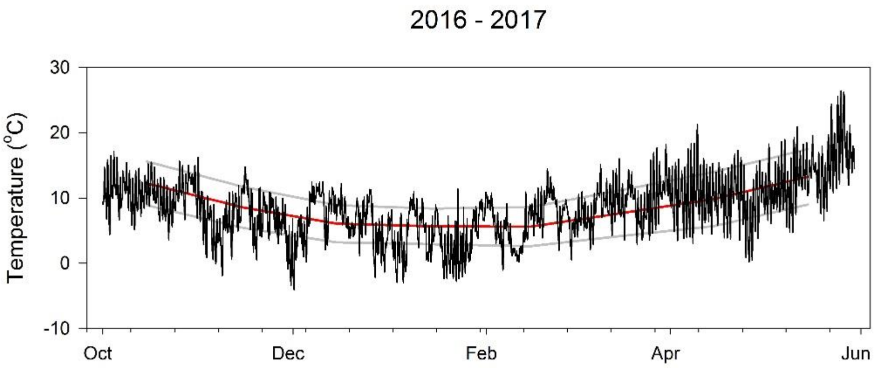


Figure 5.2 Measured outdoor air temperature in Southampton for the study periods: Y1 2015 - 2016 (top) and Y2 2016 - 2017 (bottom). Also shown is the monthly mean temperature (red) and monthly mean daily mean maximum and minimum temperature (grey) from a 1981 – 2010 baseline (Met Office n.d.)

5.1.3 Summary of indoor environment and occupant comfort

Figure 5.3 shows the indoor air temperature and globe temperature measured during each survey visit over the two year survey period. This highlights both the diversity of temperatures maintained in occupants' rooms as well as the high correlation between air and globe temperature. This includes 188 measurements from 47 participants in the first year and 22 measurements from 22 participants in the second year. The air temperature and globe temperature match very closely (correlation coefficient R = 0.995, $p<0.05$) which is common in well-insulated buildings away from direct solar or other source of radiation (Nicol et al. 2012, p.95). This confirms that the air temperature can be used with confidence instead of the globe temperature.

The range of temperatures across the visits is striking, with occupants of the same building with room temperatures between 18°C and 28°C degrees. Air velocities were found to be negligible with most survey visits resulting in mean values <0.1m/s. Relative humidity measured during survey visits over the two year period ranged from 21% and 62% and followed changes in outdoor conditions decreasing from October to April. Table 5.3 provides a full summary of the measured indoor environmental measurements taken during survey visits in both Year 1 (4 surveys) and Year 2 (1 survey). The final column shows the p-value of a one-way ANOVA across all survey visits and indicates that there are only significant differences in group means in relative humidity. Tukey HSD post-hoc tests find that the differences are significant between all groups apart from Year 1 Survey 2 and Year 2. This result is expected as it tracks the seasonal change in outdoor relative humidity.

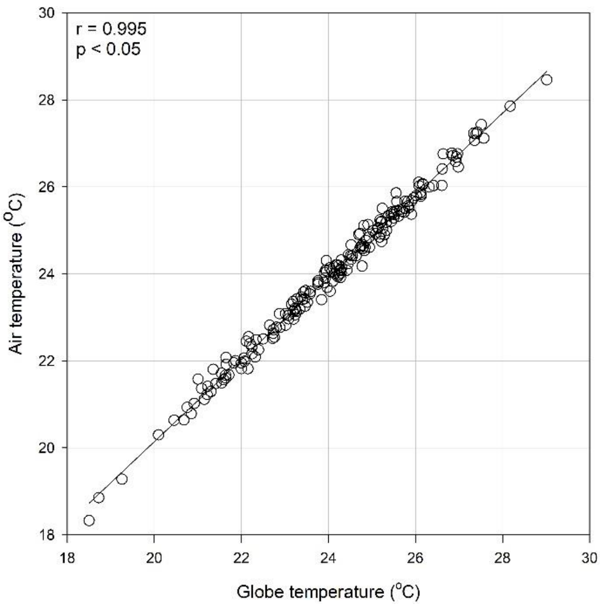


Figure 5.3 Indoor air temperature and globe temperature for all survey visits in Mayflower halls, Southampton. The correlation coefficient r = 0.995 (p<0.05) indicating a strong linear relationship.

Table 5.3 Summary of indoor environmental parameters measured during survey visits to Mayflower halls of residence showing the mean (μ) and standard deviation (σ) of key indoor environmental parameters. The p-value in the final column is the significance of an ANOVA test indicating a significant difference in relative humidity only.

	Year 1						ANOVA
	Survey 1	Survey 2	Survey 3	Survey 4	Year 2	All	p-value
Globe T (μ)	24.31	23.94	23.72	24.41	24.98	24.27	0.07
Globe T (σ)	1.68	1.83	1.78	2.18	1.60	1.81	
Air T (μ)	24.20	23.91	23.64	24.30	24.86	24.18	0.07
Air T (σ)	1.57	1.76	1.69	2.08	1.58	1.73	
RH (μ)	50.28	46.64	38.81	32.51	44.5	42.55	< 0.05
RH (σ)	5.6	5.3	6.9	6.3	6.33	6.09	
Air velocity (μ)	0.00	0.01	0.00	0.01	0.00	0.00	0.17
Air velocity (σ)	0.00	0.03	0.00	0.03	0.00	0.01	

Variability is likely to be due to the position of the room in the building complex in terms of floor level and orientation. Figure 5.4 shows the mean indoor temperature of the 47 rooms of the face to face study plotted according to floor level and orientation. Floor levels were grouped into low, medium or high, and some orientations have been grouped based on north or south being dominant. For example, the North (N) groups also include northeast and northwest orientations. Within each group there is variation in indoor temperature which indicates that factors other than the physical characteristic of the room are determining the indoor environment. This is particularly evident when considering specific examples such as the north facing rooms at low, medium and high floor level (N HIGH, N LOW, N MID). In all three sample periods, the rooms at low floor levels have relatively high temperature compared to the others which is likely to be due to occupant behaviour and preference.

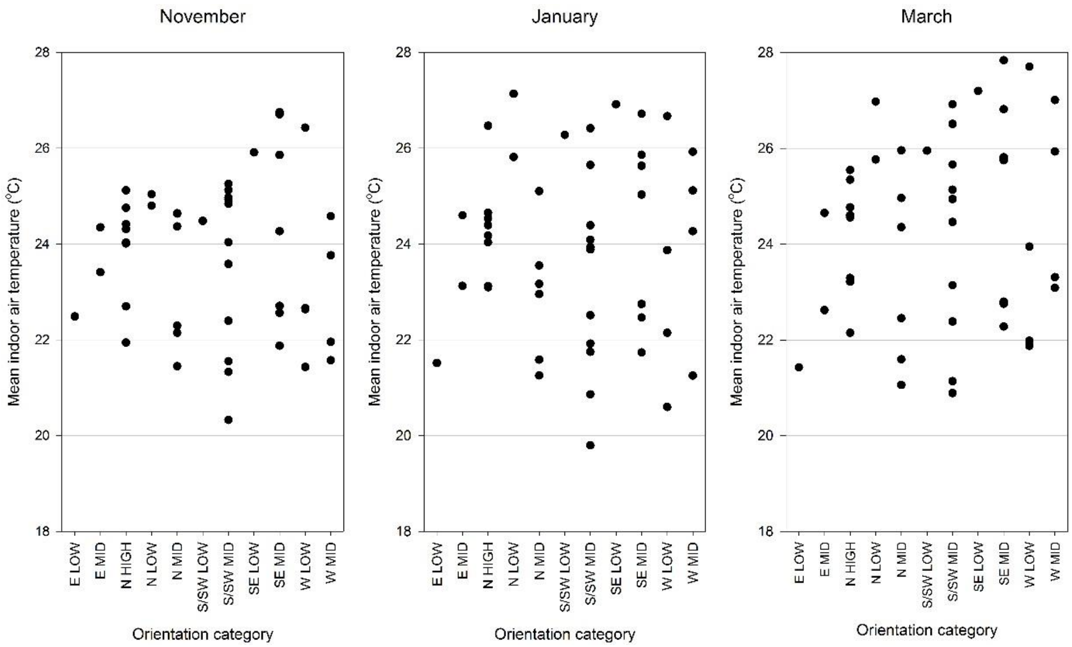


Figure 5.4 Mean indoor air temperature for 3 2-week periods in November (left), January (middle) and March (right), grouped by orientation and floor level.

The variation in indoor temperatures is matched by the variation in thermal sensation votes reported by participants as shown in Figure 5.5. Pearson product moment correlation confirms a correlation, R = 0.4, $p < 0.05$. A simple linear regression showed a significant relationship between TSV and T_g; the R^2_{adj} value was 0.16 ($p < 0.05$) indicating that globe temperature accounts for 16% of variation in thermal sensation vote. The regression line gives a neutral temperature of 22.8°C however the spread of the data indicates that this is not representative of all participants' preference. This variability in indoor thermal preference is highlighted further by the distribution of comfort temperatures shown in Figure 5.6. These comfort temperatures were determined by the Griffiths method for each data point (4 per participant) using the measurements and thermal sensation votes taken during the survey visits. The range of comfort temperatures is striking, from 16.7°C to 28.6°C across the surveys. Furthermore, 26% of the 206 comfort temperatures calculated are over 25°C and just 4% are below 20°C. This shows a greater preference for higher temperatures than assumed by the EN15251 standard which recommends 20 – 25°C during the heating season for residential spaces (CEN 2007). The range of thermal preference observed in the case study is indicative of a set of occupants with mixed expectations for their indoor environments. These expectations and behaviours may be rooted in their thermal history, as adaptive thermal comfort theory suggests.

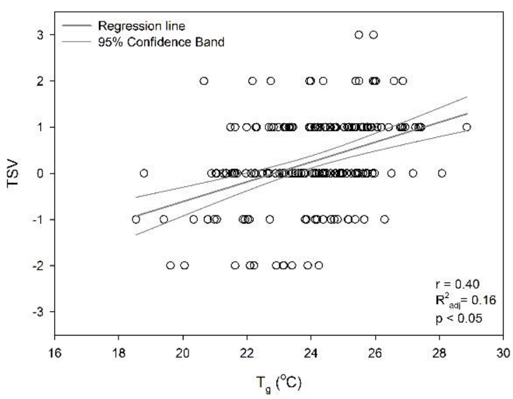


Figure 5.5 Thermal sensation votes with corresponding globe temperature for all survey visits. The correlation coefficient, r, is 0.4 and the linear regression R^2_{adj} = 0.16 (p< 0.05)

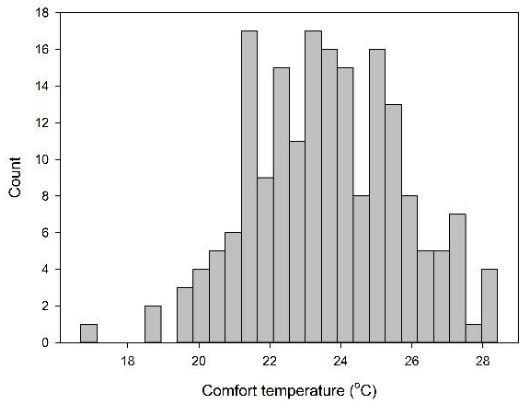


Figure 5.6 Distribution of comfort temperatures from all survey visits

5.1.4 Summary

- Variability in occupants room temperature which can't be explained by orientation and floor level alone
- Evidence of variability in occupants' thermal preference (comfort temperatures) found
- Occupants clothing related adaptive behaviour indicates that either there is a tendency to adapt their personal variables rather than their environment or that occupants are adjusting their clothing in response to difficulty in managing their environment.
- Outdoor conditions were warmer than usual for study period.

5.2 Comfort and perceptions of the indoor environment

This section further explores the variability in indoor environments and preferences of the occupants with a focus on understanding the influence of past thermal experiences on current preferences. The analysis presented here draws on data collected during the face-to-face study and individual profile study to provide a fuller picture of occupants' experiences. To investigate occupants' indoor environments, three one-week periods from the face-to-face study were selected to match the following criteria: 1) represent the environment between the four comfort survey visits and 2) during academic term time when the residence complex could be assumed to be occupied in a typical manner. The selected periods are shown in Table 5.4 alongside the dates for the comfort surveys in the face-to-face study.

Table 5.4 Year 1 study details and timeline with mean outdoor ambient temperature (weatherunderground 2016)

Month	Type	Start date	End date	Average monthly ambient temperature (°C)
October	Comfort + background survey	19/10/15	03/12/15	11.2
November	Monitoring	16/11/15	22/11/15	10.3
December	Comfort survey	30/11/15	14/12/15	10.6
January	Monitoring	11/01/16	17/01/16	5.8
February	Comfort survey	02/02/16	11/02/16	5.4
March	Monitoring	07/03/16	13/03/16	6.3
April	Comfort survey	18/04/16	27/04/16	8.5

5.2.1 Differences in thermal preference based on climate background

Figure 5.7 presents box plots of monitored indoor air temperature for each of the three selected periods grouped by climate of previous residence. Also shown is the design indoor temperature range as given by the EN15251 standard (CEN 2007). Both Categories A (cold UK) and B (warm/hot) have group mean air temperatures within the recommended range whereas the Category An (cold non-UK) group means lie above this range. Category An was found to be significantly higher than Category A in November by 2.1°C ($p < 0.05$) and higher than Categories A and B in January ($p < 0.05$), as shown in Table 5.5. The roman numerals represent statistically significant differences in comfort temperature determined by one-way ANOVA with Tukey's HSD post-hoc test ($p < 0.05$). Where the normality assumption has been violated (March), Kruskal Wallis ANOVA with Dunn post hoc test has been used. The fact that Category An group means are above the design indoor temperature range provides further indication that European standards may not be providing comfortable indoor conditions for some residents, due to differences in developed preferences (Amin, Teli, James, et al. 2016).

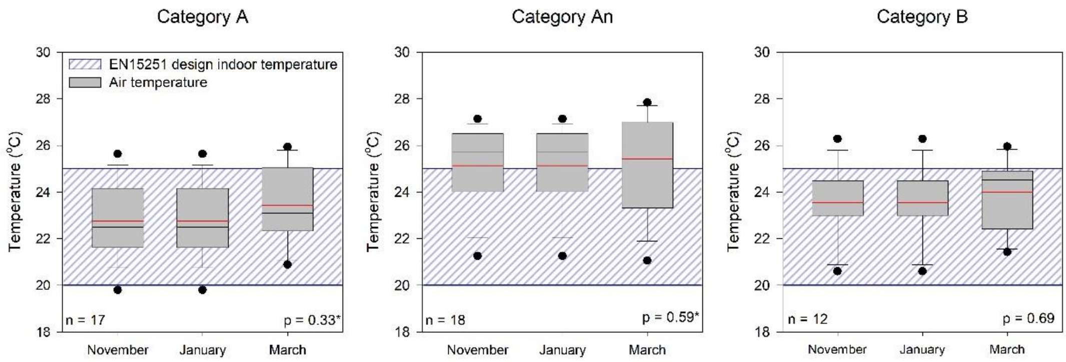


*Figure 5.7 Monitored indoor air temperature for the three selected periods grouped by climate of previous residence for Year 1. One-way ANOVA found no significant difference between monitoring periods in any Category, as shown by the p-values; * indicates where the normality assumption is violated and Kruskal Wallis ANOVA has been used.*

Table 5.5 Mean indoor air temperature grouped by climate of previous residence with ANOVA results for comparison between climate groups shown and results of Tukey HSD post-hoc tests indicated by the numerals. Where Kruskal Wallis ANOVA has been used (March) due to non-normality, Dunn post-hoc tests have been conducted.

	Indoor air temperature T_a (°C)					
	November		**January**		**March**	
	mean	**σ**	**mean**	**σ**	**mean**	**σ**
Category A	22.6[i]	1.3	22.7[ii]	1.6	23.4[iv]	1.6
Category An	24.7[i]	1.4	25.1[ii, iii]	1.7	*25.4[iv]	2.0
Category B	23.7	1.2	23.5[iii]	1.5	24.0	1.4
ANOVA p-value	< 0.05	-	< 0.05	-	< 0.05	-

[i, ii, iii, iv,] indicates statistically significant difference between pairs by Tukey HSD or Dunn post-hoc test
[*] indicates violation of normality assumption by Shapiro-Wilk test

Figure 5.8 shows the hourly averaged indoor air temperature for each room for the same three periods. Again, these are grouped by climate of previous residence (shown in colour) with the daily mean outdoor temperature included for reference (weatherunderground 2016). These provide no indication of seasonal variability in any group with indoor temperatures remaining similar from one period to the next. The stable and high temperatures from November to March indicate that the residents who are new to the UK, Categories An and B, are continuing to maintain their higher preferred temperatures rather than adapting to match the preferences of the long term residents as adaptive comfort theory might suggest. This calls into question the efficacy of passive climate chamber studies investigating adaptation times in new indoor environments as they overlook the occupants' active engagement. While it may be possible for people to adapt to new indoor conditions, if they are able to modify their environment they may instead continue to match their environment to their preferences over the long term.

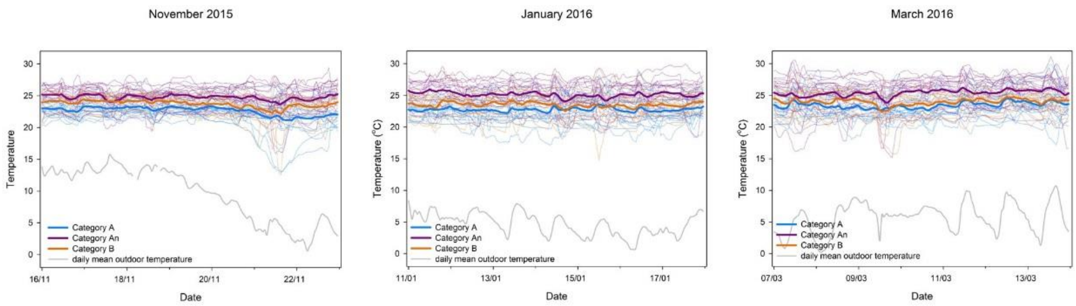


Figure 5.8 Hourly averaged indoor air temperature for each accommodation unit grouped by climate of precious residence

5.2.2 Indoor thermal history and adaptation in a new climate

Figure 5.9 shows the monitored indoor air temperature for two weeks in February 2016 for all study participants. This period was selected in order to compare to the analysis conducted in the pilot study. Due to the larger sample size and the introduction of the third climate category (An), the results highlight something different in this instance. The most noticeable feature is the higher indoor temperature kept in the rooms of Category An participants with a group mean of 25.1^{o}C. This is in comparison to a Category A group mean of 22.9^{o}C and Category B group mean of 24.1^{o}C. This difference is significant between Category A and An ($p<0.05$) determined by one-way ANOVA and Tukey HSD post-hoc test. The differences between groups are similar to those presented in Figure 5.7. This is slightly different to the results found in the pilot study where Category B participants had indoor temperature closer to 25^{o}C which may be due to the high number of participants (67%) who reported having air conditioning in their homes in their previous residence. This highlights the need for a high level of detail on users' background in thermal comfort models in order to improve predictions.

The three participants highlighted in Category A, shown in the grey box, satisfy the condition of having lived mostly in the UK for the two years prior to the study however, they have all lived the majority of their lives in different climate zones. All three of these participants maintained room temperatures closer to those of Category An or Category B. For these individuals, a 2-year threshold for living in a new climate may not be sufficient for re-adaptation given the ability to create preferred environments. Removing these three participants from the analysis leads to a Category A mean of 22.5^{o}C and introduces a statistically significant difference between Category A and B ($p<0.05$). This further highlights the depth of knowledge on participants' background required to understand thermal preference which has implications for thermal comfort research methods more broadly.

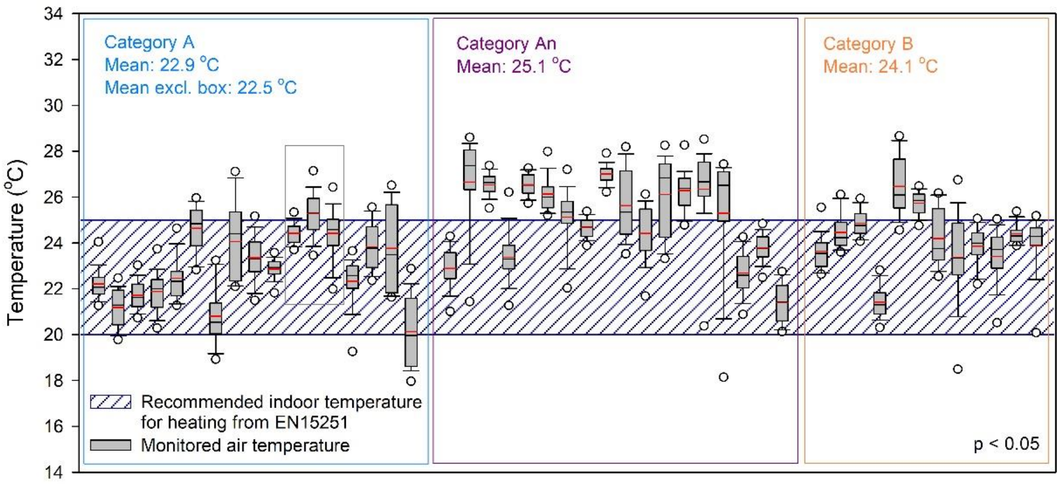


Figure 5.9 Monitored indoor air temperature of each participant for two-week period in February 2016. Participants are grouped by climate of previous residence. The results of one-way ANOVA between groups is indicated by the p-value; this difference is significant between Category A and Category An.

The background survey revealed that 94% of Category An residents had indoor space heating in their previous residence, compared to 17% of Category B residents. The familiarity with and expectation of indoor space heating could be a contributing factor to the higher observed indoor air temperatures in this group. This is consistent with other recent studies that have found that access to heating is a more significant driver for indoor thermal preferences than outdoor climate (Kalmár 2016; Luo, Ji, et al. 2016; Ning et al. 2016; Cao et al. 2011). The majority of the Category An participants (76%), are from areas of Northern China that experience very cold winter temperatures but are extensively heated. In these areas, regulation stipulates that district heating be supplied to all residences though it is common for there to be no household level heating controls (Cao et al. 2014) which leads to high indoor temperatures (Cao et al. 2014; Wang et al. 2017). It is possible that this lack of access to controls experienced in previous residences is driving a tolerance to and preference for high indoor temperatures.

The individual profiles obtained the following year allowed further investigation into this phenomenon with the use of specific case studies. Of the 22 participants, 3 were from Beijing and reported having heating in their previous residence. Figure 5.10 shows the difference between the comfort temperature and indoor air temperature for each survey submission. A positive difference represents a comfort temperature higher than the actual air temperature and a negative difference indicates a comfort temperature lower than the current air temperature. All three case studies have high indoor air temperatures and appear to find their environment comfortable, as evidenced by the narrow range of thermal sensation votes which are mostly between -1 and 1 aside from one response by participant 41. For all survey responses, participant 41 reported having the window open and in 96% of cases reported the heater being on. This style of controls use is consistent with the suggestion that occupants who are accustomed to continuous heating are continuing to manage their environment in the same way. Participant 29, on the other hand, had a low rate of heater use with it being reported as on in only 12% of survey responses compared to the window in an open state in 59% of responses. This also indicates a low rate of interaction with the heating controls which could be indicative of similar behavioural traits. Participant 11 exhibits more interaction with indoor environmental controls with the heater being reported as on in 54% of responses and windows open in 38%.

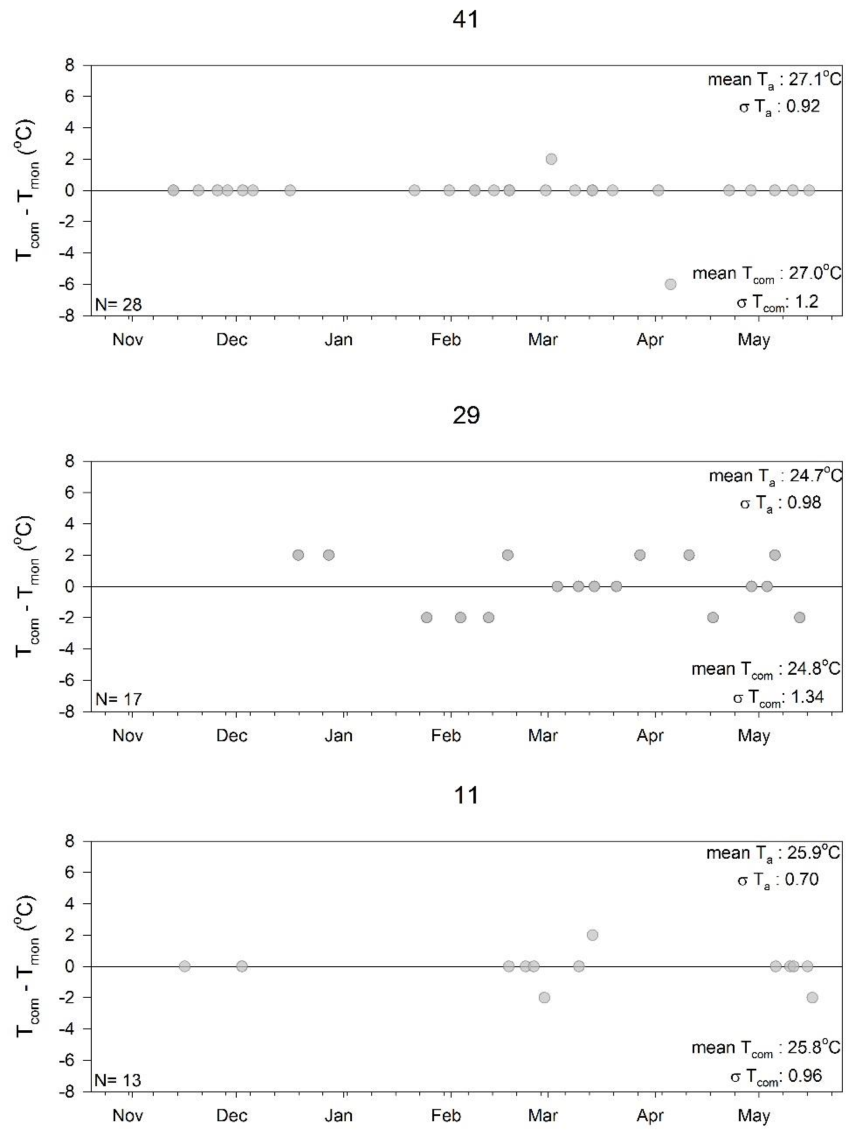


Figure 5.10 Sample of occupants previously living in Beijing, China with low variability in responses to the indoor environment in Mayflower. Each point represents the difference between the comfort temperature and actual indoor air temperature.

Figure 5.11 shows the distribution of comfort temperatures, calculated using the Griffiths method grouped by climate of previous residence. While the comfort temperatures fluctuate slightly over time, one- way ANOVA found no statistically significant difference in comfort temperature between surveys in any climate category, as shown by the p-values in the Figure. These results are also summarised in Table 5.6; the p-values in the table show the results of one-way ANOVA between Categories at each survey. The roman numerals represent statistically significant differences in comfort temperature determined by Tukey's HSD post-hoc test. Category B is found to have a significantly higher mean comfort temperature than Category A ($p < 0.05$) in the first (1.7°C) and second (2.2°C) survey conducted in October and December, respectively. On average, the comfort temperatures of Category A subjects were lower than the other two groups and well within EN15251 design values. However, it appears that all groups have slightly higher comfort temperatures in April than in February which could be an indication of seasonal adaptation to warmer Spring conditions.

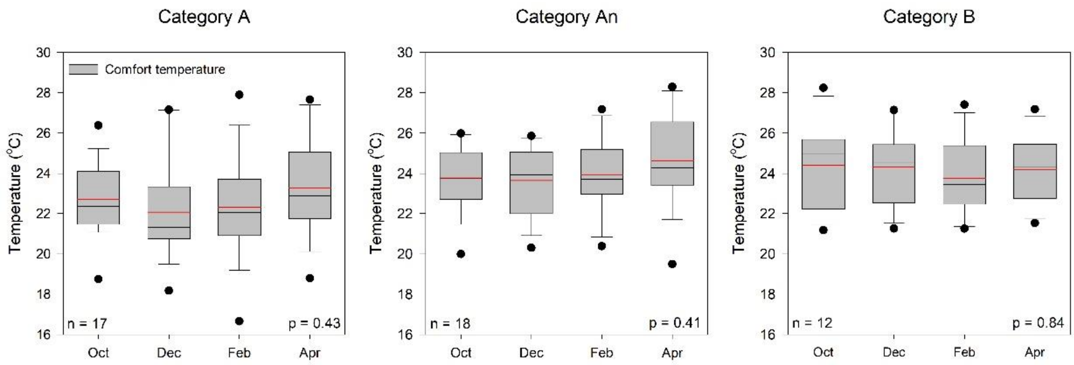


Figure 5.11 Comfort temperature for each survey grouped by climate of previous residence for Year 1. One-way ANOVA found no statistically significant difference between surveys in any climate category as indicated by the p-values.

Table 5.6 Mean and standard deviation of comfort temperatures calculated using the Griffiths method grouped by climate of previous residence. Statistically significant differences, determined by one-way ANOVA with Tukey post-hoc test, between climate groups are indicated by the numerals

	Comfort temperature T_{com} (°C)							
	October		December		February		April	
	mean	σ	mean	σ	mean	σ	mean	σ
Category A	22.7[i]	1.8	22.1[ii]	2.4	22.3	2.6	23.3	2.4
Category An	23.8	1.6	23.6	1.7	23.9	1.8	24.6	2.2
Category B	24.4[i]	2.2	24.3[ii]	1.8	23.8	1.9	24.4	1.7
ANOVA p-value	< 0 .05	-	< 0 .05	-	0.06	-	0.19	-

[i, ii] indicates statistically significant difference between groups

Since clothing adjustment is a fundamental adaptive behaviour mechanism it is possible that some insight can be gained from analysing estimated clo values of participants recorded during survey visits. Overall, mean clo values during all surveys in the face-to-face study are closer to the expected clo values during summer despite seasonal variation (Figure 5.12). Category A participants maintained, on average, lower clothing insulation levels than the other two groups with the biggest difference appearing in Survey 1. One-way ANOVA found this difference to be significant both between Category A and Category An and between Category A and Category B ($p < 0.05$) in Survey 1 only. Furthermore, the significant increase ($p < 0.05$) in clothing insulation observed in Category A between October and December, determined by Student's t-test, is interesting considering very little change in outdoor temperature. This is perhaps an indication of psychological adaption whereby occupants accustomed to the local seasonal variation come to expect, and therefore dress for, cooler temperatures. Figure 5.13 also shows that in comparison to Categories An and B, the lower clothing insulation observed in Category A coincides with lower indoor temperatures (Figure 5.16) and TSV on the cool side (Figure 5.16). This indicates a greater preference for warmth amongst Category An and Category B participants compared to Category A participants, irrespective of clothing adaptation.

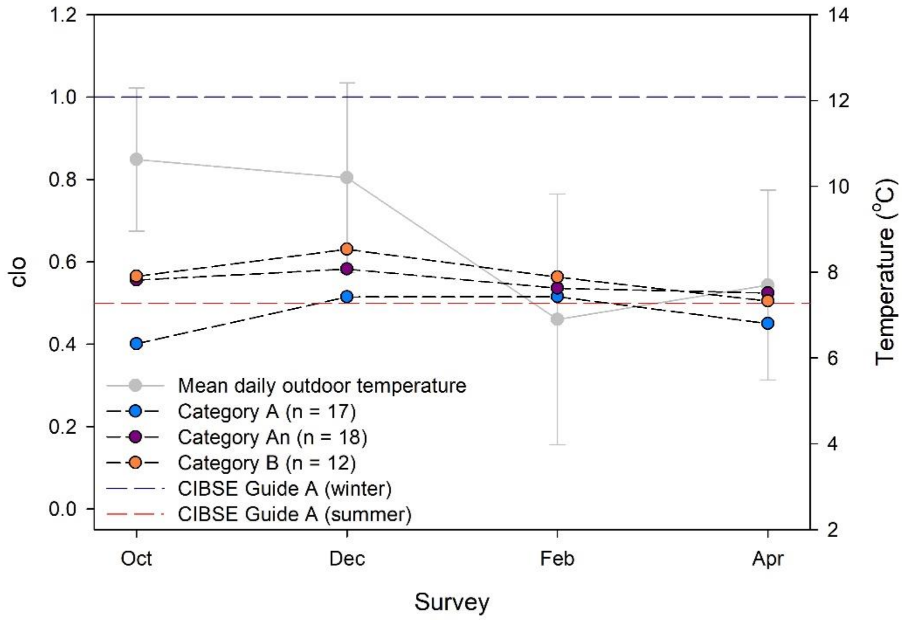


Figure 5.12 Mean clothing insulation levels (clo) of participants in each survey grouped by climate of previous residence. One-way ANOVA found a significant difference in clo between Category A and Category An ($p < 0.05$) and between Category A and Category B ($p < 0.05$) in October only. The CIBSE Guide A assumed clo value (1) for living spaces is shown in blue for winter and red for summer.

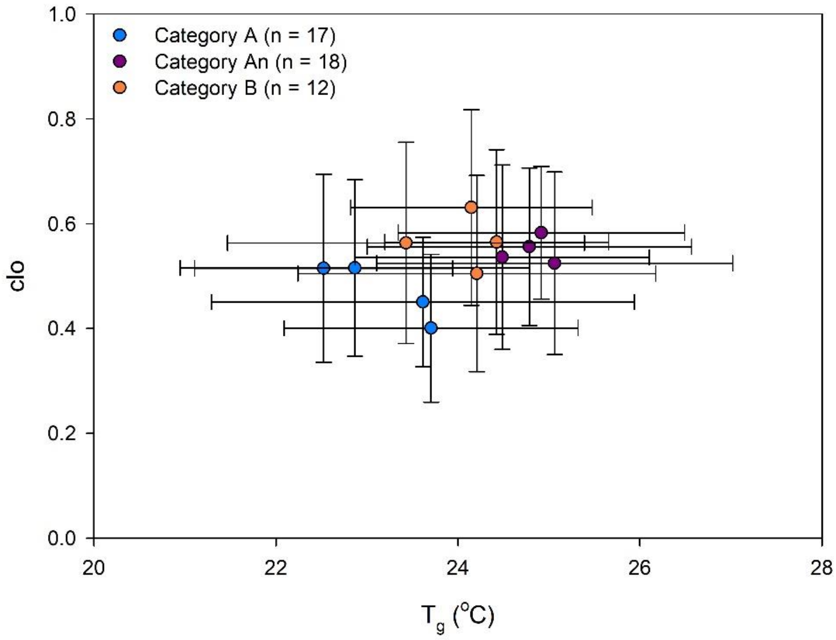


Figure 5.13 Mean and standard deviations of clothing insulation (clo) and globe temperature (T_g) for each survey

The results from the app based study revealed similar behaviour. Figure 5.14 shows the monthly mean average clothing insulation value against monthly mean indoor temperature at the time of survey submission per participant. This shows a tendency for Category A participants to maintain consistent, lower clothing insulation levels at lower indoor temperatures in comparison to the other two categories.

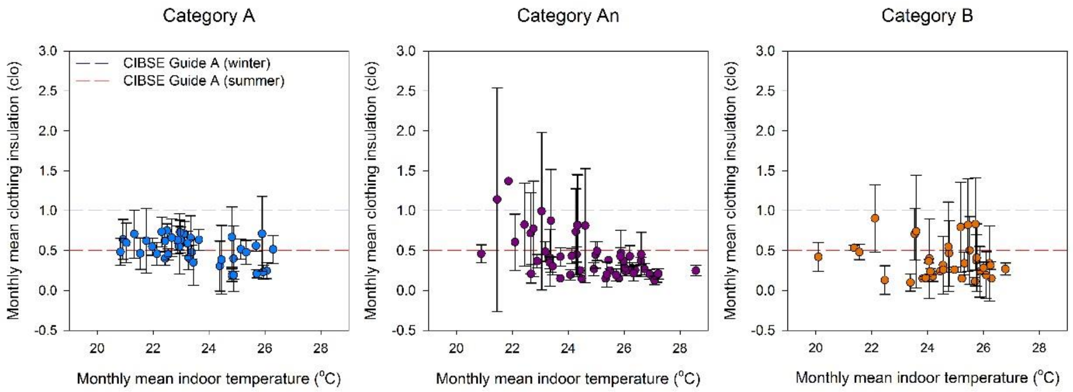


Figure 5.14 Monthly mean clothing insulation level (clo) and monthly mean indoor air temperature (at time of survey submission) per participant

5.2.3 Relationship between indoor conditions and occupant's perception

Based on the principle of adaptive thermal comfort, it is expected that indoor air temperature is closely related to comfort temperature. This assumes that individuals take appropriate actions (e.g. opening windows, turning on radiators) to maintain comfort. Figure 5.15 shows the relationship between mean indoor air temperature across the three selected monitoring periods and mean comfort temperature across all four surveys. The grey reference line corresponds to the case of 'perfect' adaptation, where the indoor temperature equals the occupant's comfort temperature. There is a significant relationship ($r = 0.58$, $R^2_{adj} = 0.32$, $p < 0.05$) between the two values when considering the whole data set (not considering climate category) which supports the assumption of the adaptive principle. For the whole sample, the R^2_{adj} indicates that 32% of the variation in monitored air temperature can be explained by comfort temperature. Category A, long term UK residents showed the highest level of correlation ($r = 0.65$, $p < 0.05$); the R^2_{adj} value of 0.38 ($p < 0.05$) indicates that 38% of variation in indoor air temperature can be explained by comfort temperature. Category An also demonstrated reasonably close correlation (0.55, $p < 0.05$) and a significant R^2_{adj} value of 0.26 ($p < 0.05$) indicating that 26% of variation in indoor air temperature can be explained by comfort temperature. Category B, however, did not show a significant relationship ($r = 0.28$, $R^2_{adj} = -0.01$, $p = 0.37$). This indicates that they are the least able to maintain comfortable conditions.

A higher degree of correlation in Category A supports a key premise of adaptive comfort theory as it indicates that those most accustomed to the local conditions, climatic and cultural, are best able to achieve comfort. Many of the Category An participants have air temperatures higher than their comfort temperature. This provides further evidence that heating controls are being used in a similar way to the district heating systems of their home country which in this context is compromising thermal comfort. Very weak correlation between comfort temperature and air temperature in Category B may be due to a lack of familiarity with the new conditions they experience, especially indoor heating systems, with only 17% having had heating in their previous residence. Overall, this suggests that indoor thermal history and familiarity with heating systems and controls are important factors in thermal comfort which has implications for adaptive thermal comfort models.

To further investigate the relationship between indoor environment and occupants' perceptions, Figure 5.16 shows the mean and standard deviation of the thermal sensation vote binned by average monthly indoor temperature. The temperature bins are the monthly mean of the spot measurements of indoor air temperature taken at the time of survey submission. One-way ANOVA found no significant difference in TSV at different temperature bins within any Category, as indicated by the p-values on Figure 5.16. Interestingly, Category A has greater variation in thermal sensation at high temperatures and Category An at lower temperatures.

This indicates that those accustomed to typical UK indoor conditions are less able to deal with the unusually high temperatures (between 26°C - 28°C). Conversely, the Category An residents' variability in thermal sensation at lower temperatures (20°C - 22°C) further supports the earlier suggestion that they may be accustomed to higher indoor temperatures. Interestingly, Category B residents, show a small standard deviation in thermal sensation across the temperature bands.

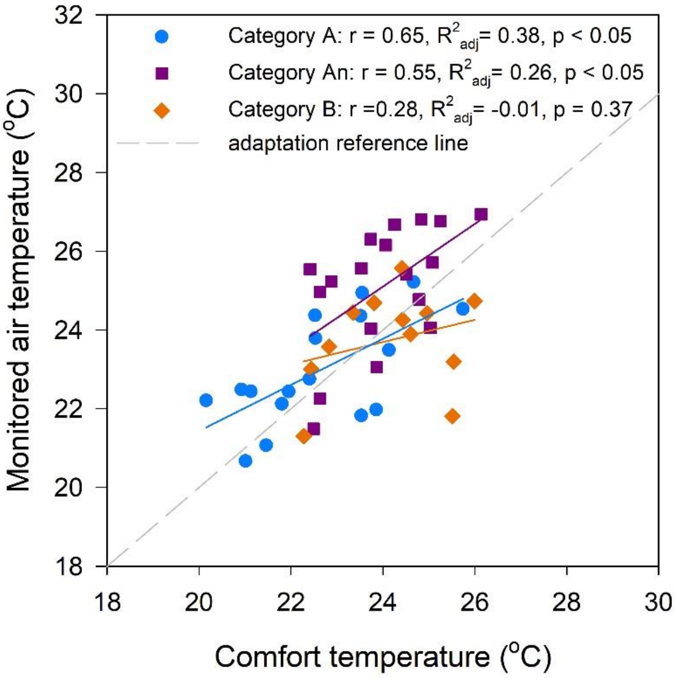


Figure 5.15 Relationship between participants' mean comfort temperature across the four surveys and mean indoor air temperature for the three monitoring periods. The correlation coefficient (r) for the whole data set is 0.58 with an $R^2_{adj} = 0.32$ ($p < 0.05$)

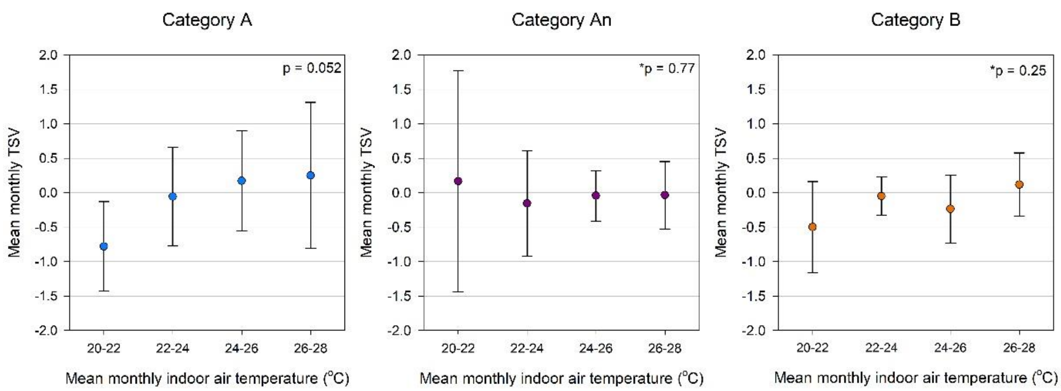


*Figure 5.16 Mean and standard deviation of thermal sensation vote at monthly average indoor air temperature bands. One-way ANOVA found no significant differences in TSV at different temperatures; * indicates where the normality assumption has been violated and Kruskal Willis ANOVA has been used.*

5.2.4 Individual variability in indoor thermal preference

Further insight about occupants' impressions of their indoor environment can be obtained from the individual profiles. Notably, these show how variable occupants' responses to the indoor temperature may be despite stable conditions. Figure 5.17 shows some of the most extreme examples of this where each point represents the difference between the comfort temperature and actual air temperature. A positive difference represents a comfort temperature higher than the actual air temperature and a negative difference indicates a comfort temperature lower than the current air temperature. All three participants shown in Figure 5.17 have a high response rate which provides many snapshots of their responses to the indoor environment. The mean and standard deviation of the indoor air temperature and comfort temperature are shown in each figure. All three of these examples show greater variability in comfort temperature, demonstrated by the higher standard deviation, than in air temperature.

Participant 14 grew up in Guyana until the age of 10 and has since lived in the UK with a typical wet central heating system in their previous residence. The comfort temperature calculated for this participant during the face to face survey visit was 22.5^{o}C, 3.2^{o}C lower than the average obtained over the course of the study period. Similarly, participant 28 has lived most of their life in the UK but was born in Malaysia and has spent every summer there. Comfort temperature at time of survey was 21.9^{o}C, 2.6^{o}C lower than the mean over the study period. Participant 19 has lived in Kazakhstan (Astana and Almaty) prior to moving to the UK, where they had a wet central heating system, similar to the heating systems typically found in the UK. At the time of the survey visit, their comfort temperature was found to be 21.7^{o}C which is considerably lower than the long term average of 24.4^{o}C.

Four time 'blocks' were created where morning was 7:00am to 11:59am, afternoon was 12:00 to 17:59, evening was 18:00 to 22:59 and night was 23:00 to 6:59am. This was used as the independent variable in a chi-squared test to see the relationship with thermal sensation vote. No evidence of diurnal variation was found however, the variability highlights the question of whether stable environments are what people want. More broadly, this indicates that future thermal comfort studies could benefit from a higher number of repeated responses in order to obtain a fuller picture of occupant comfort in residential settings.

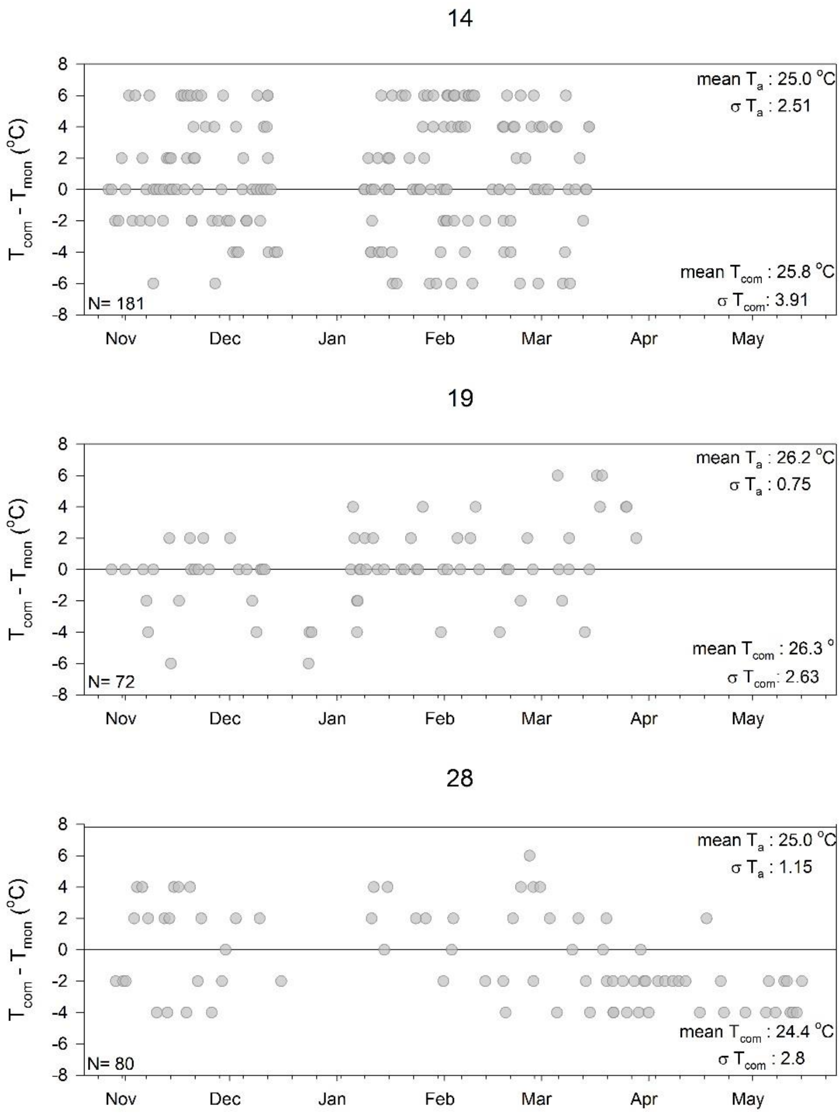


Figure 5.17 Sample of three occupants showing high variability in responses to the indoor environment. Each point represents the difference between the comfort temperature and actual indoor air temperature.

5.2.5 Use of indoor environmental controls

In addition to adjusting personal variables such as clothing, building users can modify their environment by use of heaters and windows to maintain comfortable conditions. As the discussion around variability in occupant's thermal preferences has demonstrated, this is likely to play an important role in impressions of the indoor environment.

The face-to-face study asked participants at each survey the frequency of their interaction with the environmental controls available to them in the previous two weeks. The results of these questions are shown in Figure 5.18 where 'Rarely' is once per week, 'Sometimes' is a few times per week, 'Often' is daily and 'Frequently' is more than once per day. Throughout the survey period, a large proportion of participants report high levels of interaction with the windows. Additionally, of those who reported 'Never' opening their windows, some left them open all the time. In total, 100%, 75%, 75% and 0% of those who reported never adjusting their windows said they were open all the time in survey 1, 2, 3 and 4 respectively. While self-reporting of behaviour is known to be problematic (Podsakoff & Organ 1986; Schwarz et al. 2008; Krosnick & Presser 2010), in this case it at least provides some indication of occupants perceived interactions with their environment. The high rate of interaction with the windows agrees with Andersen et al.'s (2013) findings which demonstrated that window opening frequency is higher in bedroom than living rooms. Though, due to the specific design of this type of residential building, occupants may use their rooms both as a bedroom and living space.

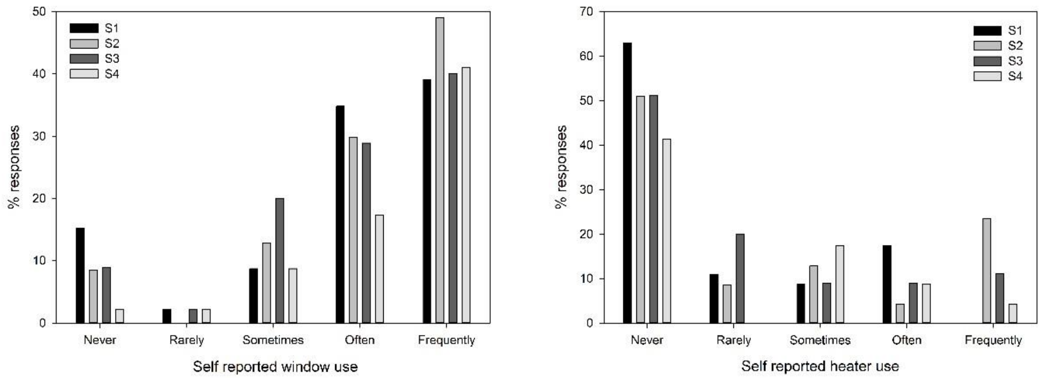


Figure 5.18 Self-reported frequency of window use (left) and heater use (right) for two weeks prior to the survey visit from the group study. 'Rarely' is once per week, 'Sometimes' is a few times per week, 'Often' is daily and 'Frequently' is more than once per week.

A large number of occupants reported never using their heater over the study period as shown in Figure 5.18. Of these, 67%, 54%, 30% and 65% reported leaving their heater off all the time in survey 1, 2, 3 and 4, respectively. Chi-squared tests revealed no significant relationship between category of climate origin and window or heater use behaviour across the four surveys, though small effects were found in individual surveys.

The app responses submitted by participants also asked about the current state of the environmental controls. The proportion of open and closed responses for each participant are shown in Figure 5.19. In contrast to the group study, these represent 'snapshots' of the current state of the controls at the time of the survey submission. Like the group study, the diversity in use of windows is evident in this smaller sample though it should be noted that the number of responses vary between participants. Participants were grouped into 'high' or 'low' heater and window users where the threshold was 50% of survey responses. Fisher exact tests found that previous residence was not a significant factor in frequency of occupants' use of windows (p = 0.86) or heaters (p = 0.42).

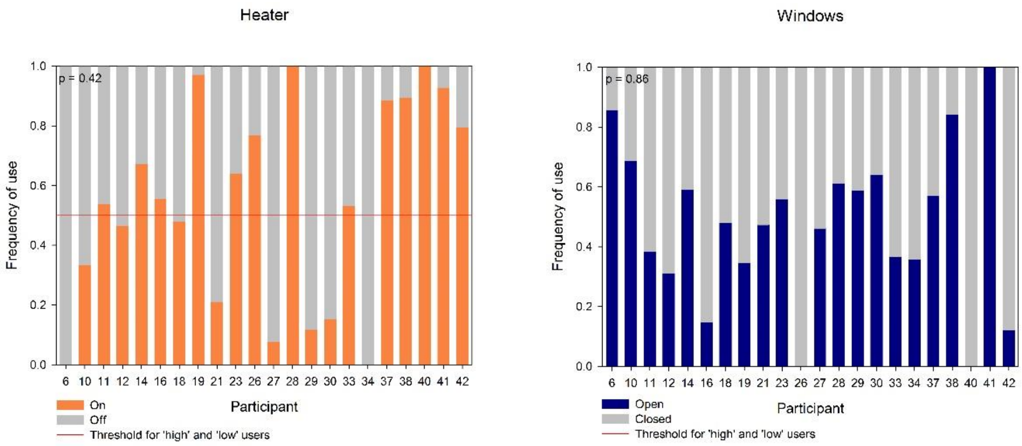


Figure 5.19 Proportion of survey responses where heater was reported as 'on' (left) and windows reported as 'open' (right) for Year 2. The Chi-square p-values indicate that climate category is not significant in determining 'high' and 'low' use.

5.2.6 Summary

- Differences observed in comfort temperatures in occupants based on climate history were observed in some surveys. On average, Category A, An and B had comfort temperatures of 22.6°C, 24.0°C and 24.2°C, respectively.
- Differences were observed in indoor air temperatures for occupants with different climate histories. On average, Category A, An and B had indoor temperatures of 22.9°C, 25.1°C and 23.7°C, respectively. These differences may be due to cultural and behavioural factors and indoor thermal history.
- Occupants with alternate indoor thermal histories may have greater difficulty managing their environment.
- There can be high degree of temporal variability in perception of the indoor environment which highlights the importance of repeated surveys.

5.3 Implications for thermal comfort models

At present, standards that deal with indoor environments for conditioned spaces are based on the steady state PMV model (ASHRAE 2013; ISO 2005; CEN 2007). This model was based on climate chamber studies conducted using a small subgroup of the population (Danish and American male students) and only takes account of physical parameters to determine comfort. This work has shown that occupants' previous experiences of indoor environments and their subsequent expectations may override this heat balance model for predicting comfort.

The adaptive model of thermal comfort is defined with a single independent variable, mean outdoor temperature and is applicable only when this is between 10°C and 33.5°C (ASHRAE 2013). This work has shown that for a region where the monthly mean outdoor temperature is less than 10°C, indoor thermal comfort is influenced by a number of other factors. These include parameters related to indoor thermal environment, controls use and behavioural habits. Indoor thermal environments are linked to outdoor climate but not in a straightforward linear way. Where heating is prevalent, people's thermal preferences will be closely linked to typical set point temperatures which can vary based on heating system type (Cao et al. 2014), income (Meier & Rehdanz 2010) and payment structure (Teli et al. 2016). Similarly, household income has been found to be directly related to residential air conditioning uptake (Davis & Gertler 2015; Biddle 2008; Santamouris 2016). In addition to this, location specific practices are likely to influence peoples' perceptions of comfort. Therefore, indoor thermal comfort can be said to be a function of all of these parameters in the following way:

$$\begin{aligned}\text{Comfort conditions} = \quad & f\,[(\text{type of outdoor climate * duration of exposure}) + \\ & (\text{type of indoor climate * duration of exposure}) + \\ & (\text{typical behaviour in previous exposure}) + \\ & (\text{familiarity with controls}) + \\ & \text{Income}]\end{aligned}$$

Figure 5.20 shows the mean and standard deviation of indoor temperature for various studies against mean outdoor temperature. The purple shaded area represents the outdoor temperature zone that current adaptive models can explain. In these locations, outdoor temperature and indoor temperature are linearly related as buildings in these climates are naturally ventilated. As the mean outdoor temperature increases beyond 35°C, air conditioning in dwellings becomes more common and therefore indoor temperatures fall and the indoor temperature range decreases due to high levels of conditioning. This is highlighted in the Kuwait study shown in green (Al-Ajmi & Loveday 2010). The wider range of indoor temperatures found in Dammam, Saudi Arabia (Alshaikh & Roaf 2016), shown in purple, is likely to be due to the vast differences in construction of the dwellings employed in the study.

In locations where lower outdoor temperatures are experienced (green and yellow areas in Figure 5.20), access to heating, both technically and financially, is key to understanding thermal expectations. For example, in Sweden, shown in Figure 5.20 in dark blue, where household income plays a less significant role due to typical payment structures and countrywide heating access policy, the indoor temperature has very little variability. Where the mean outdoor temperature is very low indoor space heating is prevalent, indoor temperatures are comfortable according to European standard, such as in Khabarovsk, Russia (blue) (Nicol 2017) and Harbin, China (maroon) (Wang et al. 2017; Wang et al. 2010b; Wang 2006; Cao et al. 2016). In contrast, indoor conditions that would be considered uncomfortably cold can be found in locations that are generally thought of as warm, such as Portugal (teal) (Magalhães et al. 2016) and Cyprus (black) (Pignatta et al. 2017). These are shown in the green shaded area which represents locations where levels of heater use is mixed, with some dwellings having no heating at all, leading to lower mean indoor temperatures.

These examples, along with the results of the field studies conducted in this work demonstrate the importance of local norms with regards to conditioning of indoor spaces for understanding thermal experiences and expectations. As indoor spaces are likely to become increasingly conditioned, in terms of air conditioning in hot climates and heating in cold climates, this is likely to become increasingly important. Any attempts to develop a generalised adaptive model for climates outside the current ASHRAE zone (10^{o}C – 35^{o}C) should consider typical indoor conditioning practices in order to understand likely thermal preferences.

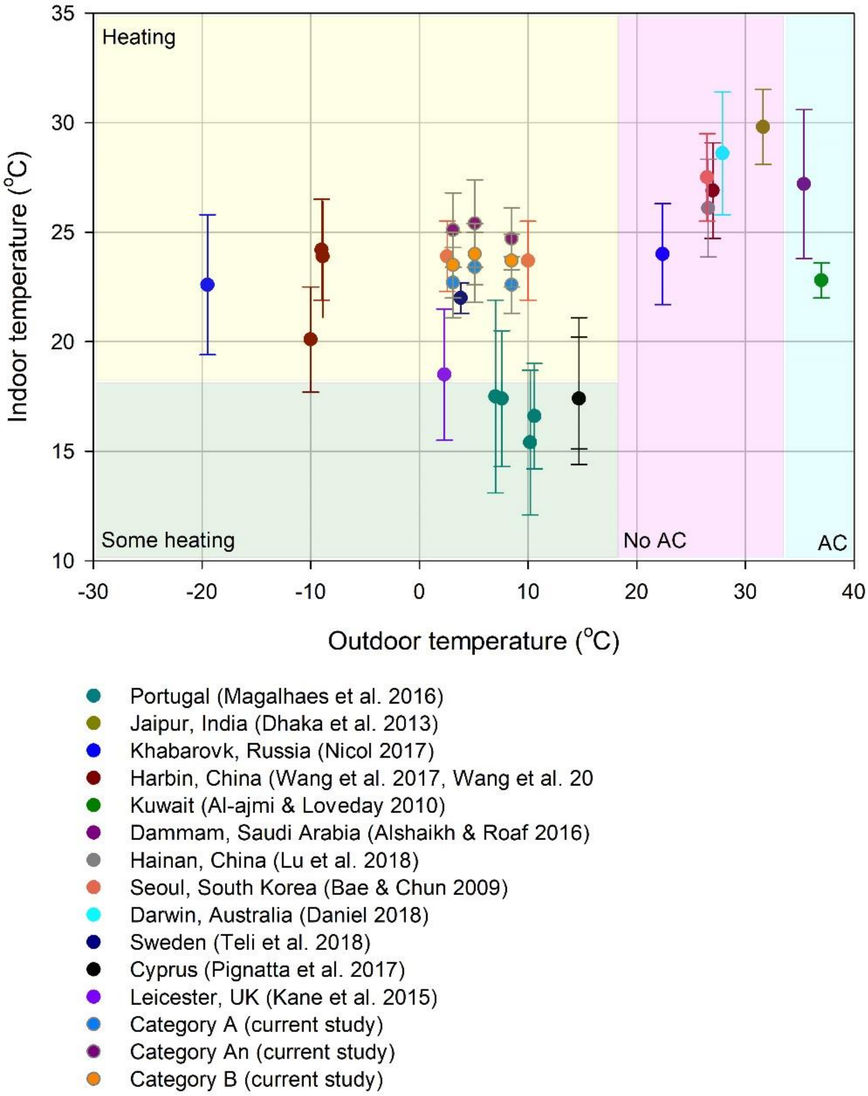


Figure 5.20 Mean and standard deviation from various residential field studies against mean ambient temperature during the study period

5.4 Multivariate analysis of thermal comfort in a new climate

A simplified version of the theoretical model described was explored using comfort temperature (T_{com}) obtained in this research as the outcome variable. Predictor variables were heating degree days (HDD) in city of residence prior to the UK, typical indoor temperatures in city of residence prior to the UK (T_{prev}) and access to heating in prior residence (H_{prev}) obtained from surveys in this research. A mathematical representation would be as follows:

$$T_{com} = a + b_1 HDD + b_2 T_{prev} + b_3 H_{prev} + \varepsilon$$

where T_{com}, HDD, T_{prev} and H_{prev} are as described above, a is the intercept, $b_{1,2,3}$ are the partial regression coefficients and ε is the error term.

For this analysis, participants from both years were considered leading to a sample size of 69; 47 participants from Year 1 and 22 participants from Year 2. Heating degree days were calculated from weather files obtained from EnergyPlus weather file database (2017) or through the European Commission Typical Meteorological Data access service (2017) using a baseline of 15.5ºC. The Typical Meteorological Year (TMY) files were downloaded in EPW format and converted to TM2 files using the CCWorldWeatherGen tool (Jentsch et al. 2013) and then read using the NREL Excel macro. For some cities in China, nearby cities were used as proxies. Using the open data sources, it was possible to find HDD data for 57 out of 69 participants.

As indoor environmental studies in residential settings are relatively rare, finding indoor temperature data to match the specific cities in which participants lived prior to moving to the UK is particularly challenging. Therefore, it was not possible to only include residential data as this would be too limiting though this would be preferable. Instead, the constraints placed on the inclusion of data were that it was collected during the heating season, (apart from cases where there is little seasonal variation) and the study did not focus on unusual construction types such as Passivhaus or vernacular building styles. These constraints were chosen since including them would not provide a representative, typical indoor environment for most occupants. Furthermore, in some instances, data was taken from a nearby city which was considered to have similar climatic conditions and, in some instances, regulations, which would mean that indoor climates are expected to be similar. This is particularly true in the case of China, where indoor heating is regulated based on climatic zone (Cao et al. 2016). Therefore, the available data sources were searched with following order of priority:

1) Residential buildings in the ASHRAE comfort database II or other published studies
2) Residential building in an appropriate, nearby city in the ASHRAE comfort database II or other published studies
3) Non-residential buildings in the ASHRAE comfort database II or other published studies

4) Non-residential building in an appropriate, nearby city in the ASHRAE comfort database II or other published studies

In total, it was possible to find an appropriate indoor temperature in the city of previous residence for 47 of 69 participants using this approach, as shown in Table 5.7. However, 24 of these participants are from the UK as shown in the table.

In order to carry out a multivariate linear regression using these three predictor variables, HDD T_{prev}, and H_{prev}, there must be a linear relationship between each of the predictor variables and the outcome variable, T_{com}. Therefore, the first step was to investigate these individual relationships. Figure 5.21 shows the scatterplot of comfort temperature against HDD in previous climate of residence. Comfort temperature across the sample varies from 20.2°C to 27.0°C with mean of 23.8°C (σ = 1.5). Heating degree days varied from 0 to 2548 with a mean of 1607 (σ = 794). The Pearson product moment correlation coefficient confirmed a relationship with a value of r = -0.31 ($p < 0.05$). A simple linear regression showed a significant relationship between HDD and comfort temperature ($p < 0.05$) though the small R^2_{adj} value indicates that only 8% of the variation in T_{com} can be explained by HDD alone. Here, HDD is used as a proxy to represent outdoor climate, where fewer HDDs indicate a warmer climate. Therefore, this result is surprising since, as shown in Figure 5.20 and other work (Nguyen et al. 2014), there is a non-linear relationship between indoor and outdoor temperature when heating and air conditioning is considered. This may be due to the sample of participants not adequately representing all the different zones shown in Figure 5.20 with some climates, such as the UK, overrepresented compared to others which can affect the results.

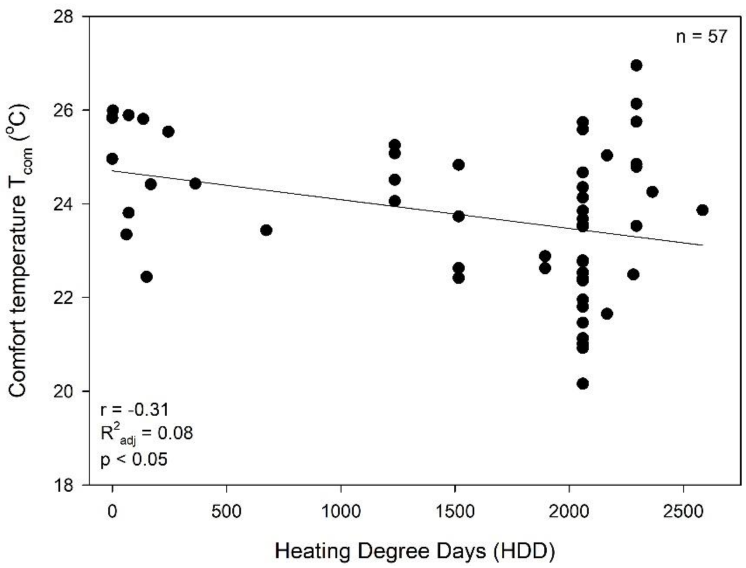


Figure 5.21 Comfort temperature against Heating Degree Days in climate of previous residence for each participant for whom data was available (n = 57). The correlation coefficient, r, is -0.31 and the linear regression R^2_{adj} is 0.08 ($p < 0.05$) indicating a significant relationship.

Table 5.7 List of countries and cities that study participants have lived in prior to moving to the UK with heating degree days (HDD) calculated from TRY files and indoor temperatures taken from existing studies with references shown; n represents the number of study participants from each location

Country	**City**	**n**	**HDD**	**Proxy city (for T_a)**	**Study type**	**T_a**	**Reference**
Canada	Montreal	1		-	office	23.04	(Donnini et al. 1996)
China	Beijing	6	2295	-	residential	21.3	(Luo, Cao, Zhou, et al. 2014)
China	Guangzhou	1	245				
China	Hangzhou	2	1237	Shanghai	residential	16.5	(Luo, Cao, Zhou, et al. 2014)
China	Huzhou	1	1237	Shanghai	residential	16.5	(Luo, Cao, Zhou, et al. 2014)
China	Nanjing	3	1517	Shanghai	residential	16.5	(Luo, Cao, Zhou, et al. 2014)
China	Ningbo	1	1237	Shanghai	residential	16.5	(Luo, Cao, Zhou, et al. 2014)
China	Shenzhen	1	135				
China	Suzhou	1	1517	Shanghai		16.5	(Luo, Cao, Zhou, et al. 2014)
China	Weihai	1	2365	Beijing	residential	21.3	(Luo, Cao, Zhou, et al. 2014)
China	Xian	2	1896	Beijing	residential	21.3	(Luo, Cao, Zhou, et al. 2014)
China	Zhangzhou	1	1785				
Cyprus	Nicosia	1	150				
Egypt	Cairo	1	168				
Guyana		1	0				
Hong Kong	Hong Kong	2	72				
Indonesia	Badung	1		Kota Kinbalu	residential	29.2	(Feriadi & Wong 2004)
	Jerusalem	1					
Jamaica	St Andrew	1	0				
Kazakhstan	Almaty	2					
Latvia		1					
Mauritius	Phoenix	1	0				
Mexico	Cuernavaca	1					

Country	City	n	HDD	Proxy city (for T_a)	Study type	T_a	Reference
Mexico	Monterrey	1					
Mexico	Puebla	1					
Mexico	Queretaro	1					
Qatar	Doha	1	6	-	office	23.8	(Indraganti & Boussaa 2018)
Switzerland	Basel	1	2281				
Taiwan	Chiayi city	1					
Taiwan	Pingtong	1					
UK	Various	24	2060	Various	residential	18.5	(Kane et al. 2015)
USA	Houston, Texas	1	674	-	residential	21.9	(Garcia et al. 2017)
USA	Sandy, Utah	1	2584	-	residential		
USA	Washington DC	1	2166	New York		18.3	(Roberts & Lay 2013)

Figure 5.22 shows the scatterplot of comfort temperature against indoor temperature in previous climate of residence. Indoor temperatures varied from 16.5°C to 29.2°C with a mean of 19.45°C (σ = 2.3). The Pearson product moment correlation coefficient indicates that there is no correlation between the two variables r = 0.06 (p = 0.69). A simple linear regression shows no significant relationship between T_{com} and T_{prev} with an R^2_{adj} = -0.02 (p = 0.69). This result is surprising since a correlation between the indoor temperatures that participants are accustomed to and their comfort temperature would be expected. However, this is likely to be an artefact of the data used. Firstly, the shortage of indoor temperature data in the specific locations required leads to an overreliance on a few studies. This can be seen in Figure 5.22 by the vertical lines of data points at 16.5°C and 21.3°C taken from a single study conducted in Beijing and Shanghai and used as proxies for other locations. Secondly, the high proportion of participants from the UK, relative to other individual locations, leads to an overrepresentation at another single value of T_{prev} at 18.5°C (Kane et al. 2015). Finally, the use of a single value to represent the indoor conditions that occupants are accustomed to in dwellings is problematic since there can be substantial variability in indoor conditions, even in a single location (Vadodaria et al. 2013; BRE 2013; Roberts & Lay 2013).

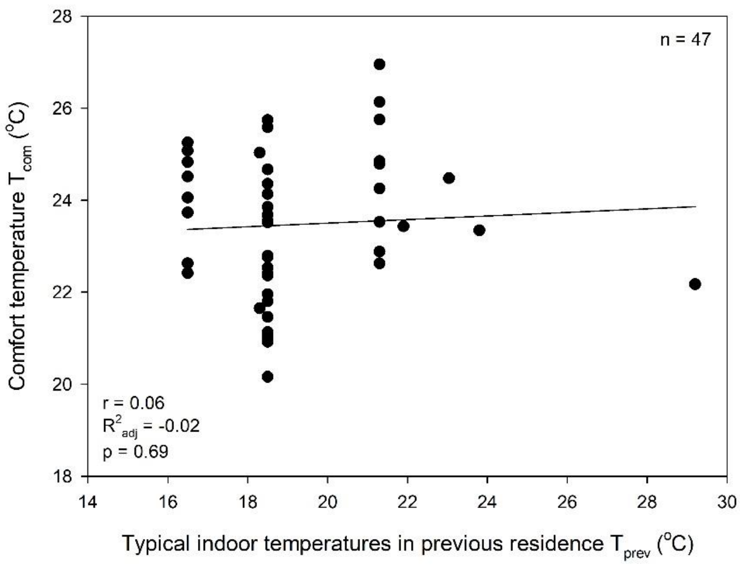


Figure 5.22 Comfort temperature against typical indoor temperature in previous residence for each participant for whom data was available (n = 47). The correlation coefficient, r, is 0.06 and the linear regression R^2_{adj} is -0.02 (p = 0.69) indicating no significant linear relationship

The final variable considered in this analysis was occupants' access to heating in their previous residence (T_{prev}). To consider access to heating as a predictor for comfort temperature in a new climate required it to be coded as a dummy variable where 0 = no heating and 1 = heating. It should be noted that this does not consider the degree of control that participants were afforded, simply whether there was heating available. This is plotted in Figure 5.23 with the recommended indoor temperature range from EN15251 (CEN 2007) shown for reference. While both group means are within the recommended indoor temperature range during the heating season, those who are accustomed to heating are closer to the middle of this range. Welch's t-test, which is more reliable with unequal sample sizes as is the case in this instance, found this difference to be significant ($p < 0.05$). Regression analysis did not confirm a significant relationship ($R^2_{adj} = 0.41$, $p = 0.051$) with a p-value just above the 95% significance level threshold. Since neither the linear regression of T_{prev} or H_{prev} as predictor variables for T_{com} were found to be significant, the multivariate regression analysis described could not be explored further.

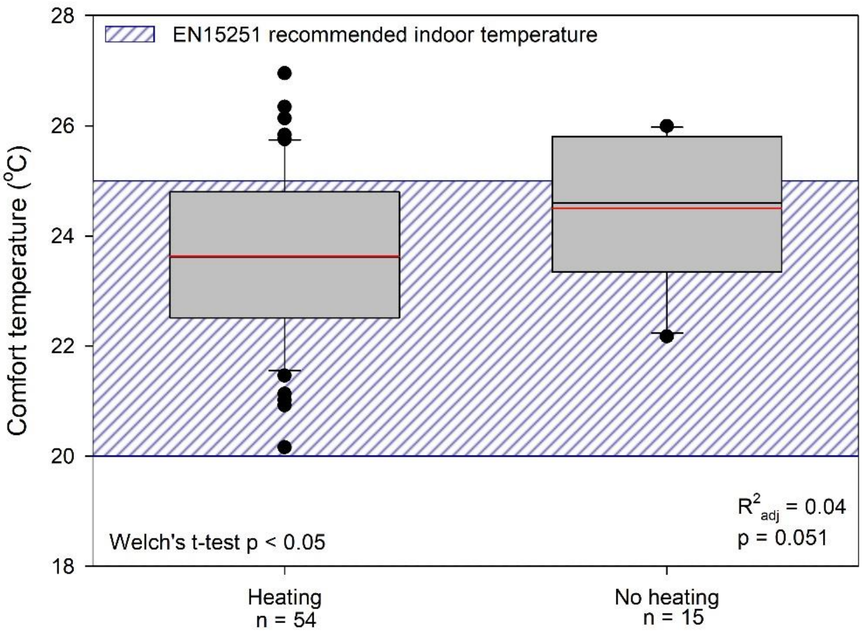


Figure 5.23 Comfort temperature grouped by participants access to heating in their previous residence. Welch's t-test found a statistically significant difference ($p < 0.05$) between groups. Linear regression did not find a significant relationship between the variables with an $R^2_{adj} = 0.04$ ($p = 0.051$).

This section has explored a practical application of the theoretical model described in Section 5.3 using three independent variables as predictors for comfort temperatures in a new climate. While there was a significant relationship between HDD and T_{com}, this was not the case for T_{prev} and H_{prev}. While there was a significant difference between comfort temperature between participants who had heating in their previous residence and those who did not ($p < 0.05$), this did not translate to a statistically significant linear regression ($R^2_{adj} = 0.41$, $p = 0.051$).

The lack of correlation between T_{prev} and T_{com}, is likely to be due to the data used to represent the indoor environments experienced in previous climates which in some instances was not residential data nor was it from the same city. This is due to a general lack of indoor temperature data availability. Furthermore, the use of a single value for all occupants from an area is problematic since, as discussed in Section 5.3, there are a number of factors that are likely to impact dwelling temperature, such as income level. The cohort used in this study is likely to be at the higher end of the income spectrum in their home countries, since they are attending university abroad, and this is not considered when using a country average value for indoor temperature experiences. Furthermore, studies have found age of construction and type of dwelling (house or flat) to be significant in determining indoor temperature (BRE 2013); this could easily be incorporated into the present study design through the questionnaire survey in the future. In this case, use of existing studies is not suitable as it does not properly account for variability in indoor temperature. For this type of model to be explored further, it would be necessary to monitor the dwelling environments of participants before their move to the UK and use this value as the input for T_{prev}. This could form an approach for future work in the field of thermal comfort.

Chapter 6

Results & Discussion: Energy implications

This section outlines the validation of the TRNSYS model which was then used to estimate the energy use for space heating associated with a range of occupancy and ventilation scenarios at difference set point temperatures. These temperatures were selected to reflect the variety of temperatures maintained by occupants of Mayflower. Finally, the model was used to estimate the potential energy savings associated with room allocation based on occupants expected thermal preferences.

6.1 TRNSYS model validation

The model was validated against metered data for heat imported from the district heat network which includes heating required for hot water. The monthly heat usage for June, a month where no space heating is provided, was taken to be the heat requirement for hot water for each month of the year. Deducting this from the total heat used in each month of the heating season (October – April) gave the total heat used for space heating. This was divided by the estimated floor area of the heated spaces (accommodation rooms and kitchens) to give 73 kWh/m^2/y where the number of heating degree days (HDD) for this winter were 1532. For reference, Passivhaus certification requires a maximum of 15 kWh/m^2/y for space heating (BRE 2011).

For validation, the temperature set point of the TRNSYS model was assumed to be 23^{o}C. While most design models would assume 21^{o}C, the data collected during the field study indicated that few occupants maintained this temperature with many keeping higher temperatures. Occupancy was also estimated based on data collected during surveys which highlighted the varied nature of residents' occupancy hours. On weekdays, occupants were assumed to be out from 08:00 - 11:00 and 14:00 – 18:00. During weekends, occupants were assumed to be out from 12:00 – 18:00. Windows were assumed to be open during daytime occupied hours on weekdays and between 10:00 – 22:00 on weekends. This gave a final space heating value of 70 kWh/m^2 where the CIBSE weather file has 1747 HDD. Adjusting the model to the lower HDD observed during the 2015-2016 (1532) winter gives a value of 61.4 kWh/m^2. This means that the adjusted space heating value obtained from the TRNSYS model is within 20% of the metered space heating demand making it a representative model. The difference in modelled and actual space heating usage may be due to the excess heat loss results from the lobby entrances to each block which functions as transitional spaces. Additionally, air change rates may be higher in kitchens when extract fans are used and the model used a single value for all spaces.

6.2 Energy performance under different occupancy and ventilation scenarios

The dynamic simulation model was used to explore the energy implications of diversity in occupant preference and behaviour. The indoor monitoring and comfort surveys conducted in this study indicate that occupants are satisfied with a wide variety of indoor temperatures in their living spaces. Furthermore, there was found to be great diversity in how occupants use their indoor environmental controls to maintain their indoor environment. These factors will inevitably have an impact on the energy performance of the building.

Since there is very little existing understanding of student occupancy patterns, and survey results revealed a wide variety of occupancy hours amongst residents, a set of hypothetical occupancy schedules were developed. The ventilation profiles developed are also hypothetical since the stable temperatures observed in the occupants' rooms could not provide a clear set of profiles. However, some occupants did show a clear pattern of daily window opening behaviour in the morning. Hence, this was used as the high ventilation (V2) scenario. The full set of scenarios with descriptions are shown in Table 6.1. These scenarios are intended as a representation of a possible maximum and minimum with the majority of occupants expected to be relying on strategies somewhere in between.

Table 6.1 Summary of occupancy and ventilation scenarios used to explore energy implications of diversity in occupant preferences

	Type	Description (occupied/ventilated hours)
Occupancy	O1: Low	Weekday: 22:00 – 08:00, 18:00 – 19:00 Weekend: 22:00 - 10:00, 16:00 - 19:00
	O2: High	Weekday: 17:00 – 13:00 Weekend: 16:00 – 12:00
Ventilation	V1: Low	Weekday: 18:00 – 20:00 Weekend: 09:00 – 10:00, 18:00 – 20:00
	V2: High	Weekday: 08:00 – 23:00 Weekend: 08:00 – 23:00

Each combination of the hypothetical scenarios in Table 6.1 were run at 1°**C** heating set point intervals from 18°**C** – 27°**C** and weighted by orientation to give an average space heating value (kWh/m²) for Mayflower. The results are shown in Figure 6.1. The measured space heating value, shown in red, provides an average value for the whole building complex however, this does not account for the variability within the building which is evident from the data collected in this study.

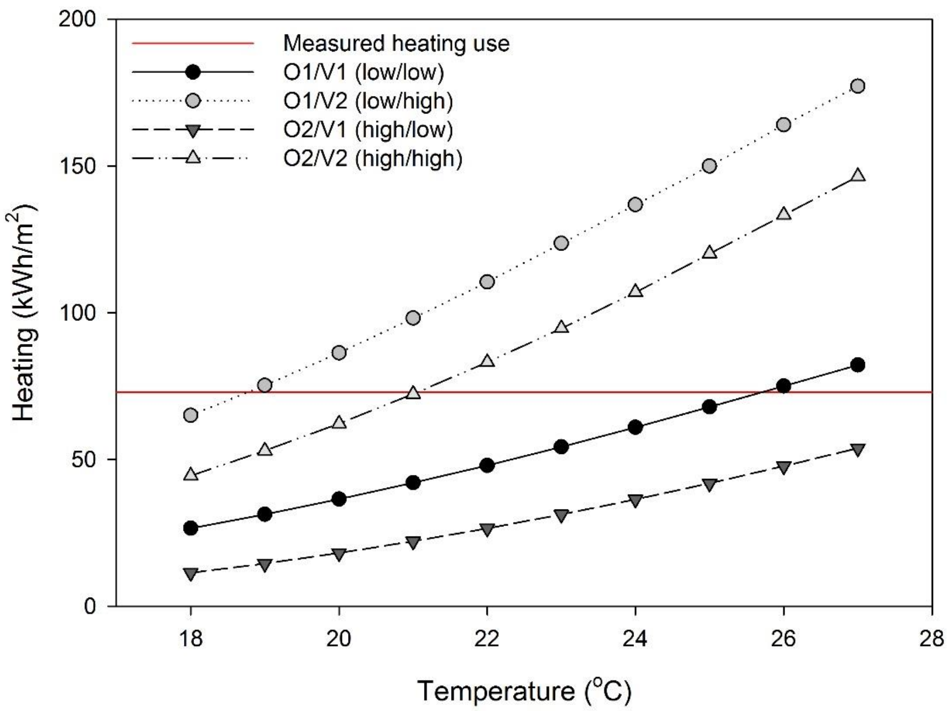


Figure 6.1 Modelled space heating (kWh/m²) requirement for Mayflower halls under different heating and occupancy scenarios adjusted for the difference in heating degree days (HDD) in the CIBSE weather file (1747) and the actual heating degree days for the 2015-2016 winter (1532). The red line represents the actual space heating use for the 2015-2016 winter calculated from the measured heat supplied to the complex.

Ventilation has a stronger influence on space heating demand than occupancy, between 40 kWh/m^2 and 100 kWh/m^2, depending on the temperature set point. This equates to between 2.2 and 3.9 times as much energy for space heating under the same occupancy scenario. The indoor monitoring data collected shows that occupants are living at this wide variety of temperatures however the results from the model highlight how this can impact the energy performance of the building depending on the behavioural strategy being employed. It is also important to note that the driver for window opening and closing behaviour is not limited to achieving thermal comfort. Other common drivers include: perceived air quality (Andersen et al. 2009; Calì et al. 2016), perceived noise level (Andersen et al. 2009) and time of day (Calì et al. 2016; Stazi et al. 2017; Fabi et al. 2012). Therefore, while it is unlikely that occupants who are maintaining high temperatures are ventilating as much as the high scenario (V2) models, it is possible that they are ventilating at a higher rate than the low scenario (V1) with motivations other than the thermal environment. The internal gains associated with high or low occupancy hours results in a difference of between 17 kWh/m^2 and 30 kWh/m^2 in space heating requirement. This is equivalent to between 1.2 and 2.3 times as much energy required for space heating under the same ventilation strategy, depending on the temperature set point. Overall, this highlights the magnitude of the variation in space heating requirement resulting from occupant behaviour which could have implications for building management.

6.3 Facade selection based on expected thermal preference

Field study results have shown that occupants are maintaining a variety of indoor temperatures which can be linked to the climate – indoor and outdoor – that they have been accustomed to prior to moving to the case study site. A high number of occupants maintaining indoor temperatures higher than expected to maintain comfort may have a considerable effect on the space heating demand. One possible strategy to mitigate these effects on space heating demand would be to place occupants in rooms which are likely to match, by design, their preferences for indoor environment. For example, placing occupants who are moving to Southampton from a warm climate on a facade which will receive higher levels of solar gain. Clearly, this solution is only suitable in certain cases, like student halls of residents, that are managed centrally and occupants backgrounds are known to the management before the tenancy period.

Figure 6.2 shows the range of space heating requirement at different temperatures based on the facade orientation. As expected, the range of heating requirement increases with higher set point temperature with the highest energy saving potential being 61kWh/m^2 assuming the same occupancy pattern and ventilation strategy. This is shown in Figure 6.2 by the green range at 27^{o}C. This indicates that there are potential energy savings associated with placing occupants in rooms that are likely to match their existing preferences.

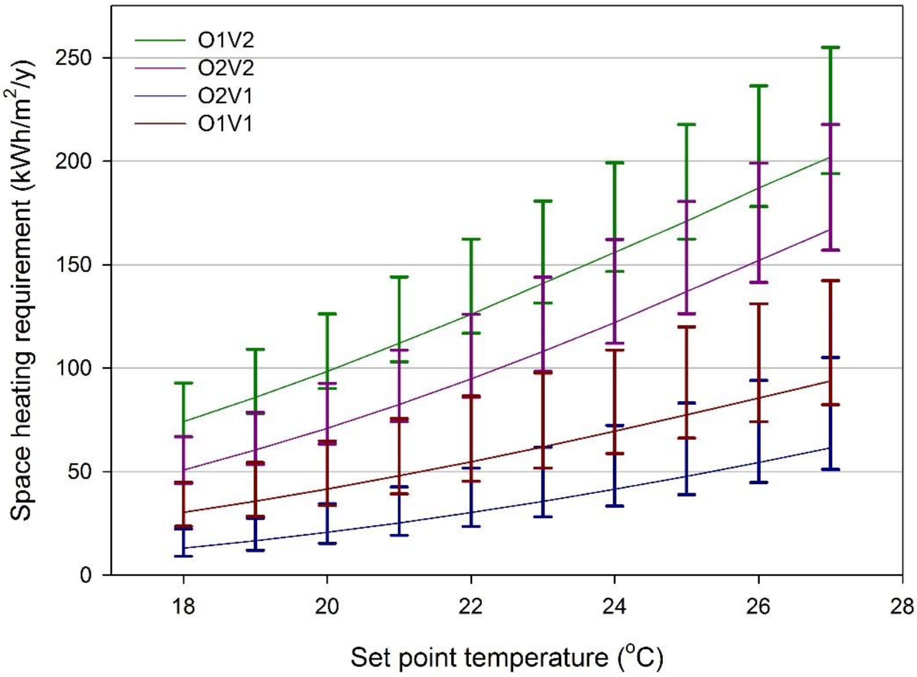


Figure 6.2 Range of space heating requirements at different temperatures based on facade orientation. The caps show the minimum and maximum possible space heating based on orientation and floor level and the line running through each scenario shows the area weighted mean space heating requirement.

To quantify the energy implications of arranging occupants to suit their indoor thermal preferences, each of the possible 39 TRNSYS outputs were grouped into either low, medium, or high categories for energy consumption based on the space heating requirement at 23°C under scenario O1V1. The binning prioritised an equal number of outputs per group resulting in 26% of Mayflower rooms classed as low, 41% as medium and 32% as high. A weighted mean space heating requirement was then calculated based on the number of rooms on each facade at set points of 23°C, 24°C and 25°C; these are shown in Table 6.2. These temperature set points were selected as they were found to be the mean indoor temperatures for Category A, B and An, respectively, as shown in Figure 5.7. An estimation of Mayflower occupants previous residence was taken from the online POE survey which found that 73% of occupants were from the UK (Category A), 20% from warm climates (Category B) and 7% from cold non-UK climates (Category An).

Table 6.2 Area weighted mean space heating requirement under occupancy and ventilation scenario O1V1 as described in Table 6.1

Heating set point (^oC)	**Space heating requirement ($kWh/m^2/y$)**		
	low	**medium**	**high**
23	54.8	66.6	74.5
24	62.0	78.6	81.4
25	69.7	87.0	90.0

The initial assumption is that occupants are placed randomly across the low, medium and high energy facades as shown at the top of Figure 6.3. This would mean that 73% of each of the low, medium and high energy facades would be occupied by Category A occupants, 20% by Category B occupants and 7% by Category An occupants. If occupants from Category An and B, who were found to have higher average indoor temperatures, were instead located on the low energy facades, as shown at the bottom of Figure 6.3, an energy saving of 0.75% could be achieved. This was estimated as the difference between the area weighted average space heating requirement of the 'before' and 'after' scenarios assuming that Category residents maintain 23^oC, Category B maintain 24^oC and Category An 25^oC on whichever facade they are located. While the energy and subsequent cost savings may be low, the impacts for building users may be significant as they may more easily be able to achieve a thermally comfortable indoor environment.

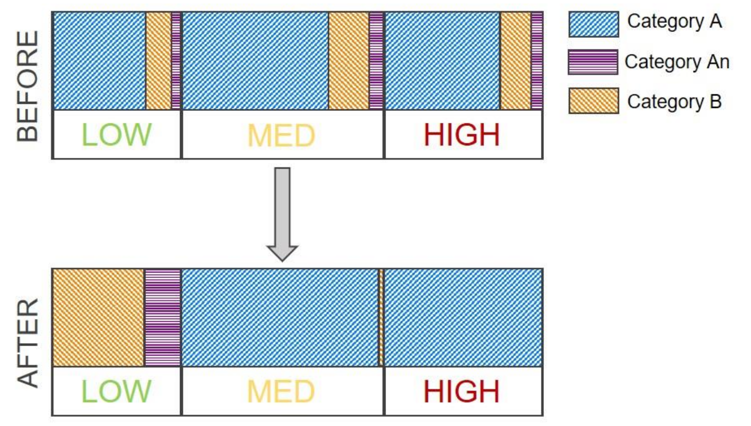


Figure 6.3 Description of facade selection based on occupants expected thermal preference

6.4 Summary

- The TRNSYS model developed estimated energy for space heating within 20% of the metered space heating use at an assumed average indoor temperature of 23^oC when adjusted for difference in heating degree days.
- Occupancy and ventilation strategies can have a substantial effect of energy requirement for space heating with a maximum of ~150 $kWh/m^2/y$ in the most extreme case.

- Room orientation can influence space heating requirement by up to 61 $kWh/m^2/y$ depending on the set point temperature.
- Assigning occupants rooms based on their expected thermal preference has the potential to save up to 0.75% space heating requirement.

Chapter 7

Conclusions

7.1 Summary of findings

This work presented results from a pilot study and two consecutive field studies in a multi-occupancy residential building with the aim of investigating the influence of moving from one climate to another on occupants' current thermal preferences. The field studies collected both subjective responses and indoor environmental measurements with one study comprised of four rounds of face to face surveys and the other with weekly (or more frequent) remotely submitted smartphone app surveys. Participants were grouped into Categories based on their location of previous residence for the two years prior to living in Mayflower halls, Southampton, UK: Category A represented UK residents, Category An represented residents from other cool/cold climates and Category B represented residents from warm/hot climates.

Survey visits showed that occupants' indoor environments differed considerably with measured air temperatures ranging from 18^{o}C – 28^{o}C. Furthermore, room orientation and floor level were not found to be driving factors in determining indoor temperature. Surveys also revealed that determining an occupancy profile for this type of building is likely to be difficult due to the wide range of self-reported occupancy hours.

Monitoring data revealed significant differences in mean indoor temperature between Category A and An in the November 2015 monitoring period and between A and An and A and B in the January 2016 monitoring period. Additionally, there was no evidence that occupants from other climates were moving towards maintaining indoor temperatures closer to the UK norm. Instead, given the choice, there was a tendency to continue to create preferred higher temperature environments. Information on occupant's previous climate also provided evidence that a 2 year threshold for living in a new climate may not be sufficient for re-adaptation. Furthermore, this raised the question as to whether or not buildings designed for UK or European standards are able to meet the comfort needs of international residents.

Comfort temperatures obtained during four survey visits also found that Category B residents had significantly higher comfort temperatures than Category A residents in October and December surveys. On average, UK students had lower clothing insulation values in all four surveys though the difference was small. The steepest change was seen in Category A clothing insulation levels from October to December 2015 which may be a result of these students, accustomed to the UK climate, expecting and therefore dressing for, colder weather. Category A participants had the strongest relationship ($r = 0.65$, $p < 0.05$) between comfort temperature and mean monitored indoor air temperature which provided further evidence of adaptation. Category B had no significant correlation ($r = 0.28$, $p = 0.37$) which may be due to a lack of familiarity with their new indoor environment, particularly the heating system. Repeated survey responses obtained using a smartphone app highlighted the temporal variation in temperature preference with some occupants demonstrating high levels of variability in preference.

The importance of indoor thermal history and familiarity with heating systems was evident in much of the analysis aimed at understanding thermal comfort preferences. Therefore, this work suggested that any future adaptive models should take these, as well as outdoor climate, into consideration. As indoor spaces are likely to become increasingly conditioned, for cooling in hot climate and heating in cold climates, this will inevitably play a considerable role in providing and managing comfortable indoor spaces.

An exploration of a conceptual model for comfort in conditioned spaces used heating degree days, indoor temperatures from existing studies and heating availability in previous residence as predictor variables for comfort temperature. No significant relationship was found between indoor temperature in previous climate and comfort temperature or between heating availability and comfort temperature. This is likely to be due to the fact that the indoor temperatures from existing studies are unlikely to accurately represent the actual indoor environments that participants are accustomed to. Therefore, actual monitored temperatures from previous dwellings would be required for this to be explored further.

A TRNSYS simulation model was used to investigate the energy implications of diversity in indoor room temperatures under hypothetical occupancy and ventilation scenarios. The simulation found that variable indoor temperature, occupancy and ventilation had a considerable impact on energy use for space heating. This could have implications for building management in similar buildings if they are not expecting such a mix of indoor thermal preferences. The model was also used to investigate the potential energy savings associated with locating students on facades which best match their indoor thermal preferences. For example, locating a student moving from a hot climate onto a facade which receives higher levels solar gain which would make it easier to match their indoor environment to their preferences. The overall heating saving was found to be small (0.75%) in this instance though the absolute energy saving per annum could be more significant in lower quality constructions such as is typical of the older building stock. More importantly, it could provide better opportunities for occupants to achieve comfort.

To summarise, the contribution to existing knowledge resulting from this work are threefold. Substantively, there are significant differences in comfort temperature and actual indoor temperature maintained by residents from different climates. Theoretically, in conditioned indoor spaces, the heat balance model for predicting comfort may be overridden by past experiences and the subsequent expectations. Methodologically, this work proposed a new model for comfort in conditioned spaces using heating degree days, indoor temperatures in previous dwelling location, and heating access in previous dwelling to predict comfort temperature. The results of this suggest that using indoor temperatures found in existing studies is not suitably accurate to represent dwelling temperatures that occupants are accustomed to.

7.2 Key findings and practical implications

Indoor air temperature

> Significant differences were found between the actual monitored air temperatures of occupants from difference climate categories with Category A maintaining the lowest. The mean indoor temperature for Category An occupants was 25.1°C which suggests that the recommended indoor temperature range of 20°C - 25°C provided by EN15251 may not be adequately be providing comfort for all occupants. This variability in actual conditions should be considered by policy makers for future guidelines and energy modellers when estimating actual indoor environments. Furthermore, a preference for higher temperature could lead to unreliable POE feedback which facility managers should be aware of.

Adaptation to new environments

This research found no evidence of change in indoor temperature preferences, given the freedom to control the environment, within 6 months. This indicates that without an additional external driver (such as cost of heating) past experiences of indoor environments and the related behaviours are important factors in understanding thermal comfort. Researchers may need to consider this in future study design to more accurately understand occupants' comfort related practices. This is also likely to have practical implications for facilities managers with regards to understanding energy use. This knowledge could also feed into the building handover approach with tailored information on appropriate building controls use.

Model for thermal comfort in conditioned spaces

This work explored a multivariate model for thermal comfort in a new climate using heating degree days, indoor temperatures in previous dwelling location, and heating access in previous dwelling to predict comfort temperature in conditioned spaces. While the limited amount of suitable data meant this was limited in its scope, it has demonstrated a new approach to researchers. Furthermore, it highlighted the importance of understanding study participants actual prior dwelling environments through monitoring for understanding a 'baseline' since existing studies cannot always account for all the variable factors determining dwelling temperature.

7.3 Study limitations

Although conducting field studies with large residential samples is understandably challenging, this is required for both internal and external validity. This study presented a modest sample size (n=47 in Year 1 and n=22 in Year 2) which can threaten the internal validity of the study in terms of statistical power and effect. Furthermore the narrow demographic of the participants, particularly in terms of age and income, is likely to jeopardise the external validity of the study. As is the case with all volunteer based studies, there is an opportunity for self-selection bias to be introduced which could impact the internal validity of the study; this is also true of study drop out. Additionally, it is possible that participants' responses to interview questions were affected by the survey process. This is known as the 'Hawthorne effect' and can also affect internal validity. Some of these factors are virtually impossible to eliminate entirely in studies such as this which require occupants subjective responses, though some, such as sample size could be addressed in future work.

Due to the short occupancy periods in the case study complex, typically matching academic years, the investigation period for readaptation is short (6 months). While this provides useful insight into the initial perceptions of new residents, a longer term study would result in further information on the process of 're-adaptation'. However, the results obtained from the remote app highlighted the importance of repeated comfort responses in understanding variability in occupant's perceptions.

The app based survey responses obtained during this study highlighted the need for repeated surveys in order to understand variability in preferences over time. However, this introduced challenges in comparison between occupants as the number of submissions varied greatly. As app based studies become more common, thermal comfort research should develop standard practices for normalising individuals' responses for different numbers of submissions.

The TRNSYS simulation model indicated that there was a wide range of space heating demand based on both set point temperature and occupancy/ventilation scenario however the model made a number of assumptions. More accurate space heating predictions could be achieved by using occupancy data based on monitored results and ventilation estimates could be improved by using monitored window use behaviour. Accurate data relating to occupant building use continues to be a challenge for the energy modelling field in general which needs to be addressed moving forward.

The estimation of potential energy savings associated with allocating rooms based on expected thermal preferences predicted a small saving in heating demand. The proportion of students from each climate Category was assumed to be the same as the online POE survey. While the survey response rate represented ~20% of the total number of Mayflower occupants, it is possible that self-selection bias may have been introduced resulting in skewed proportions.

This work has shown the importance of indoor thermal history and controls use in determining thermal comfort conditions. Currently, there are no existing indoor environment standards that incorporate adaptive principles in conditioned spaces though the principles still apply. Any future work aimed at developing such a model should account for these parameters in order to better establish comfortable indoor environments.

7.4 Recommendations for future work

To expand this work, there are several possible avenues to explore, these include:

- Detailed understanding of occupants' use of controls using accelerometer on windows and Thermostatic Radiator Valves (TRV) and temperature sensors on heaters. This would lead to greater understanding of the way in which habits formed in 'home' climates translate into new settings.
- Occupancy monitoring using passive infra-red (PIR) or CO_2 as a proxy. This would enable more accurate, evidence based inputs for energy simulation resulting in more accurate results.

- Full season thermal experience using wearable technology (such as a sensor watch) to record thermal experiences throughout the day (thermal gradients), including travelling around the city and in lecture theatres etc. This would allow exploration of the impact of everyday thermal experiences on expectations in the home.
- Data on occupants indoor dwelling temperature in their previous residence would enable further exploration of the multivariate model for thermal comfort in a new climate. This could be through emerging home technologies such as Nest.

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Appendix A

Publications

I – Energy & Buildings journal paper

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The influence of a student's 'home' climate on room temperature and indoor environmental controls use in a modern halls of residence

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Abstract

Adaptive comfort theory states that over time people adapt to their normal environment. Therefore, people from different climates are expected to have different thermal preferences and behaviours, which could lead to 'performance gap' in buildings with occupants of diverse climate backgrounds. This study investigates the influence of occupants' thermal history on use of controls and indoor temperature preference in a newly built halls of residence building complex in Southampton, UK, which provides 1104 rooms to international and UK students. A total of 223 questionnaire responses along with monitored temperature data and thermal comfort surveys from 30 rooms are used in this analysis.

The results indicate that residents' 'home' climate is impacting the reported use of environmental controls in rooms with similar typological characteristics. The average indoor temperature of residents from warm climates was 2.3◦C higher than that of residents from cool climates in February 2015 (winter heating season). This difference cannot be explained by room orientation alone. Comparison of room temperatures to design values indicates that UK design standards may not account for the comfort needs of residents accustomed to warmer climates. A simple management approach to comfort optimisation is suggested, locating students on the appropriately orientated facade to reflect their 'home' climate.

Keywords: thermal comfort, thermal history, thermal preference, occupant behaviour, controls use, adaptive comfort, performance gap

1. Introduction

As increasing efforts are made to improve the energy efficiency and subsequent emissions of buildings, a phenomenon known as “performance gap” is being observed to a greater extent. The performance gap is best described as the difference between the actual and the expected energy consumption [1]. Broadly speaking, the performance gap can be attributed to three factors; (i) design assumptions and modelling, (ii) construction and build quality and (iii) users (including management) [1]. This paper focusses on the role of users and of design assumptions regarding indoor temperatures on the energy performance of a modern halls of residence building.

As Grandclément et al. [2] indicate, energy use in buildings is socio-technical whereby users take a more active role than merely being passive receivers of design strategies. Given this, it becomes necessary to understand how users interact with the indoor environment and furthermore to address diversity in these interactions. Numerous studies have investigated the contribution of occupant behaviour on energy use and have found it to be a significant factor, though the degree of significance varies from study to study [3,4,5,6,7]. A key driver of user behaviour in the indoor environment is achieving comfort and thermal comfort in particular is seen as the most significant contributor to overall user satisfaction [8].

1.1 Thermal comfort and adaptation

A number of standards and guides have been developed in order to help designers meet the comfort needs of occupants such as ASHRAE 55 [9], ISO 7730 [10], CEN Standard EN15251 [11] and CIBSE Guide A [12]. These standards were primarily based on the heat balance approach to thermal comfort developed by Fanger [13] which uses the Predicted Mean Vote and Percentage Predicted Dissatisfied (PMV/PPD) indices. However, Fanger’s model, developed from climate chamber studies with American and Danish students, has been criticised for not adequately reflecting the variability in comfort temperatures found in field studies around the world [14]. This has led to the development of an alternative approach to thermal comfort known as adaptive thermal comfort.

Adaptive thermal comfort theory states that people take actions to restore their thermal comfort in order to compensate for changes in their thermal environment [14]. The theory also appreciates that comfort temperatures are likely to be influenced by recently experienced climate conditions and that occupants are more likely to achieve comfort when they have control over their local environment. Additionally, thermal sensation is said to depend on outdoor climate and the expectations it creates about the indoor environment [15]. The thermal adaptive mechanisms can be distinguished into three categories [16]:

a) Behavioural—behavioural adjustments include actions that aim to improve the indoor climate or the thermal state of the body and can be personal (e.g. clothing and posture changes, activity, moving to different locations), technological (e.g.

opening/closing windows or blinds, controlling fans or HVAC systems) or cultural (e.g. schedule adjustments or dress code).

b) Physiological—physiological adaptation includes all the physio- logical changes that result from the exposure to climate and that can lead to greater tolerance to the climatic conditions.

c) Psychological—psychological adaptation refers to changed perception due to past experience. Having adapted one's expectations to the indoor conditions experienced results in occupants having greater tolerance to temperature fluctuations.

de Dear and Brager [16] concluded, based on results from field studies, that the contribution of physiological adaptation or acclimatisation in explaining the difference between the comfort levels of occupants in naturally ventilated and air condition buildings was negligible. However, some studies have shown that repeated exposure to hot or cold environments can result in physiological adaptation or acclimatisation [17,18,19]. One such study, conducted by Yu et al. [19] investigated the difference in physiological responses between subjects accustomed to air conditioned and naturally ventilated indoor environments in 'heat shock' scenarios. With the small sample employed (10 in each group, air conditioned and naturally ventilated), Yu et al. [19] found that those accustomed to naturally ventilated environments did not report feeling as hot or uncomfortable as the AC group.

A further study by Yu et al. [20] investigated the long term impact of access to indoor heating on levels of physiological response by considering sub groups from Shanghai and Beijing separately. This is based on Chinese legislation which stipulates that indoor heating systems be installed only if more than 90 days in the year see a mean air temperature of 5 ◦C or less [20]; Beijing does fall under this category and thus indoor heating is common whereas Shanghai does not. This study presented 2 significant findings: (i) the skin temperature of the participants from Shanghai decreased faster than those from Beijing, which indicates a greater degree of vasoconstriction and (ii) participants from Beijing presented significantly more instances of shivering, which implies that they require more extreme homeostatic mechanisms to maintain core body temperature [20]. Since Shanghai experiences warmer winters than Beijing and therefore has no indoor heating, these findings suggest that indoor thermal history is more significant than outdoor thermal history in determining physiological acclimatisation [20].

In contrast to physiological adaption, the significance of behavioural and psychological adaption in determining comfort temperatures remains uncontested. Thermal comfort field studies have been carried out across the world for decades and it has been shown repeatedly that indoor comfort temperatures can vary in different local climate conditions [21,22,23]. This is explained by a combination of behavioural and psychological adaptive processes. Moreover, many studies in hot and humid climates have shown that occupants of naturally ventilated buildings have a wider range of comfort temperatures than those in air conditioned buildings. This provides further evidence of the importance of past experience and expectations of the indoor environment in determining thermal comfort [24,25,22,26,27].

It is evident that past experiences and exposure to a specific climate, both indoor and outdoor, can impact occupant behaviour and indoor temperature preference. Students in the UK come from various locations around the world having experienced very different climatic conditions. Their diverse thermal and cultural history could have an impact on their adaptive behaviour when they move into a UK halls of residence. This study aims to investigate the level of diversity in indoor temperatures and use of indoor environmental controls and to explore factors which may be influencing this with a focus on climate history. This has been done using a case study building; Southampton University's newly built Mayflower Halls of Residence complex, which was completed in the summer of 2014 and first occupied in September of the same year. Southampton is a major port city with a population of 250,000 located 120 km south west of London.

1.1 Mayflower Halls of Residence case study

The Mayflower Halls of Residence complex is comprised of 3 separate buildings providing a total of 1104 rooms; Fig. 1 shows a general plan of the three buildings and their orientation. The majority of rooms are single occupancy, ensuite rooms, arranged in cluster flats with shared kitchen/living room area where the number of rooms per flat varies; a small number of accommodation rooms are studio flats. The buildings are naturally ventilated with individual heating controls in each room (0–5 dial on radiator) and top opening tilt windows. It should be noted that all utility bills are included with the price of the rent so there is no financial incentive for the residents to be energy conscious with respect to heating. As part of the planning conditions for the development, this building was required to undertake a Post Occupancy Evaluation (POE) within one year of occupation; some of the results from the POE are used in this study. Fig. 2 shows a thermal image of the south east facade, as indicated in Fig. 1, taken in March 2015. The image was taken before sunrise to eliminate the influence of solar radiation on the results. The ambient temperature at the time the image was taken was 5 ◦C. As can be seen in the figure, there is significant heat loss from the open windows with rooms displaying varying degrees of window opening; some closed, some fully open and some partially open. This shows a variable use of indoor environmental controls, in this case window use pattern, which as various authors have indicated [28,4] can have implications for buildings energy performance. This paper further investigates the variability in window opening and heater use behaviour of students through questionnaires and indoor environmental measurements.

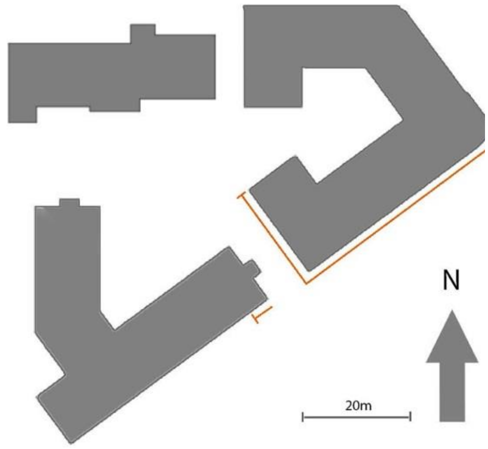

Fig. 1. Schematic diagram of the layout of Mayflower halls of residence complex located in Southampton, UK. The orange lines highlight the south east facade shown in Fig. 2

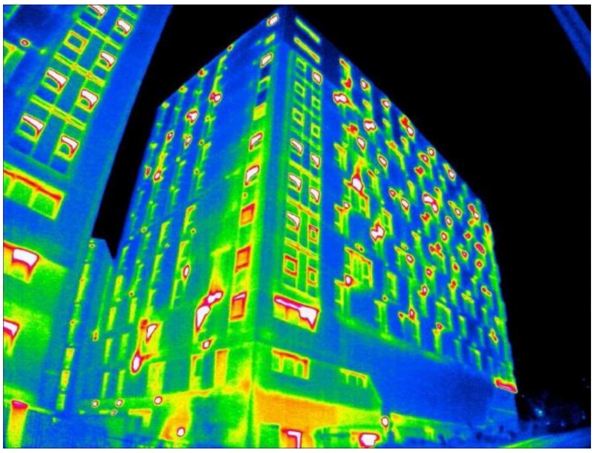

Fig. 2. Thermal image of south east facade of Mayflower halls of residence taken before sunrise on 19/03/2015 as highlighted in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The following two sections of this paper (Sections 2 and 3) are divided into two sections. 'Part 1–Online Survey' uses the results from an online POE questionnaire to understand diversity in use of indoor environmental controls. 'Part 2–Environmental Monitoring and Thermal Comfort Surveys' considers monitoring of temperature and humidity in conjunction with the same questionnaire to investigate in more detail and with a smaller sample, indoor air temperature and factors which may influence this. Thermal comfort surveys are also included in this section.

2. Methodology

2.1 Part 1–Online Survey

An online post occupancy evaluation questionnaire was sent by email to 955 (out of a total 1029) residents of Mayflower Halls of Residence in March 2015 using the University of Southampton's iSurvey software. The online survey, approved by the University ethics review committee, consisted of questions relating to the occupants level of satisfaction with the building in general, their opinion on the indoor environmental conditions in their bedroom, use of indoor environmental controls such as heating, window opening, curtains and artificial lighting and some details about them. This resulted in 223 questionnaires returned representing a response rate of 22%.

Participants were asked which city they had mostly been living in for the two years prior to moving into the case study building. These responses were then broadly grouped into "cool/cold" (Category A) or "warm/hot" (Category B) climates based on the Köppen-Geiger climate classification system [29]. Category A climates were taken to be any warm temperate, snow or polar climates with corresponding cool, cold or polar temperature classification based on winter temperatures. All others were considered to be Category B climates. In all cases, the category was decided based primarily on the average winter temperatures. The aim of this system of classification is to group participants into those who have regularly experienced winter as cold as or colder than the average UK winter and those who have not. Fig. 3 shows the previous location of residence ('home' climate) for the 220 respondents who provided an answer to this question. The blue dots represent those from Category A climates (174 respondents) and the orange dots represent those from Category B climates (46 respondents).

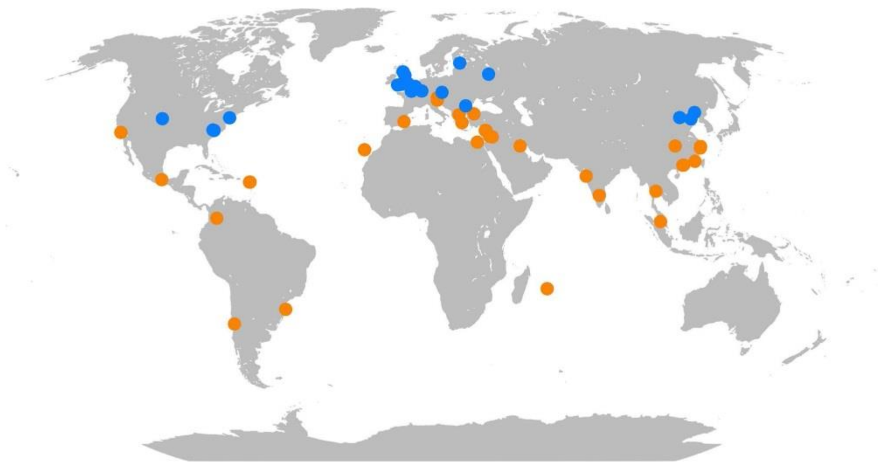

Fig. 3. World map showing previous residence of online POE survey respondents for the two years prior to living in the case study building where the blue dots represent Category A(cool/cold climates) and the orange dots represent Category B (warm/hot climates). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2 Part 2–Environmental Monitoring and Thermal Comfort Surveys

Temperature and relative humidity data loggers (MadgeTech RHTemp101A) were placed in 78 rooms in Mayflower Halls in November 2014; these 78 participants were specifically excluded from participating in the online POE survey outlined in Section 2.1. Rooms were selected based on position in the building complex so as to provide a representative sample taking account of floor level and orientation in all 3 buildings. The data loggers recorded single reading measurements of temperature and relative humidity every 5 min and were placed in one of two positions in each room depending on layout of the room and ease of access. The locations were chosen such that they remained out of direct solar radiation and to cause as little disruption to the occupants as possible.

These 78 participants were then contacted in May 2015 in order to carry out the POE questionnaire, conduct a thermal comfort survey and arrange collection of the data loggers. The questionnaire was largely identical to the online POE survey outlined in the previous section (Section 2.1) with an additional section addressing thermal comfort at the time of the survey. For the assessment of thermal sensation, the 7-point ASHRAE scale was used [9] with a 5-point thermal preference scale. The questionnaire survey was conducted in conjunction with indoor environmental measurements of air temperature, relative humidity, globe temperature and air velocity using the portable DeltaOhm HD32.3 instrument. Comfort temperatures, T_{com}, were calculated using the Griffiths method which uses the globe (operative) temperature, T_{op}, measured during the face-to-face questionnaire along with the thermal sensation vote. The Griffiths constant is taken to be 0.5 [30]:

$$T_{com} = T_{op} + TSV/0.5 \qquad (1)$$

where T_{op} is the operative temperature at the time of the survey and TSV the thermal sensation vote. A total of 30 residents took part in the interview questionnaire resulting in 30 complete questionnaires (including thermal comfort responses) with corresponding temperature and humidity data for the 5 previous months. Fig. 4 shows the location of residence of these 30 participants for the two years prior to moving into the case study buildings, grouped into Category A (cold/cool) and Category B (warm/hot) climates and represented by the blue and orange dots respectively.

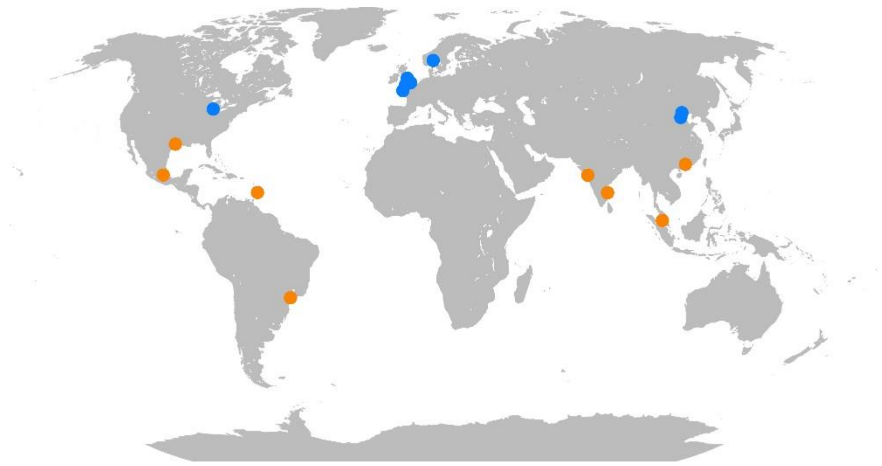

Fig. 4. World map showing previous residence of 30 environmental monitoring participants for the two years prior to living in the case study building where the blue dots represent Category A(cool/cold climates) and the orange dots represent Category B (warm/hot climates). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results & Discussion

3.1 Part 1–Online Survey

Of the 223 respondents to the online survey, 123 (55%) were female, 96 (43%) were male and 4 (2%) did not state. The age of respondents ranged from 18 to 52 with 139 (62%) being 18–19, 61

(27%) being 20–24 and 21 (9%) being 25 or over; 2 respondents' (1%) ages are not stated. The number of hours reportedly spent in the bedroom (i.e. their private space) including sleeping time on a typical weekday and typical weekend day are shown in Fig. 5. This indicates a highly irregular occupancy profile distribution in comparison to office buildings or households with some respondents reporting spending less than 5h in their bedroom and others reporting 23h; this represents a standard deviation (σ) of 3.1. It is possible that some of the responses that indicated a very low number of occupancy hours were due to a misunderstanding of the question on the part of the participants such that sleeping time was not included in their response despite the question stating that it should be. Greater variation in number of hours spent in the bedroom is evident on a typical weekend day with responses varying from 0 to 24 and a standard deviation (u) of 4.6. Observing such variation in number of reported occupancy hours indicates clearly how challenging this type of building is to predictively model. It would be unrealistic to hold it to any of the existing occupancy profiles for residential buildings where occupancy hours are taken to be in the region of 13h for a working couple or 20h for a retired couple [31] as shown in Fig. 5. This in part may be due to the mixed use of such buildings where bedrooms serve also as study and social spaces and where students' lecture schedules vary greatly especially between degree programs.

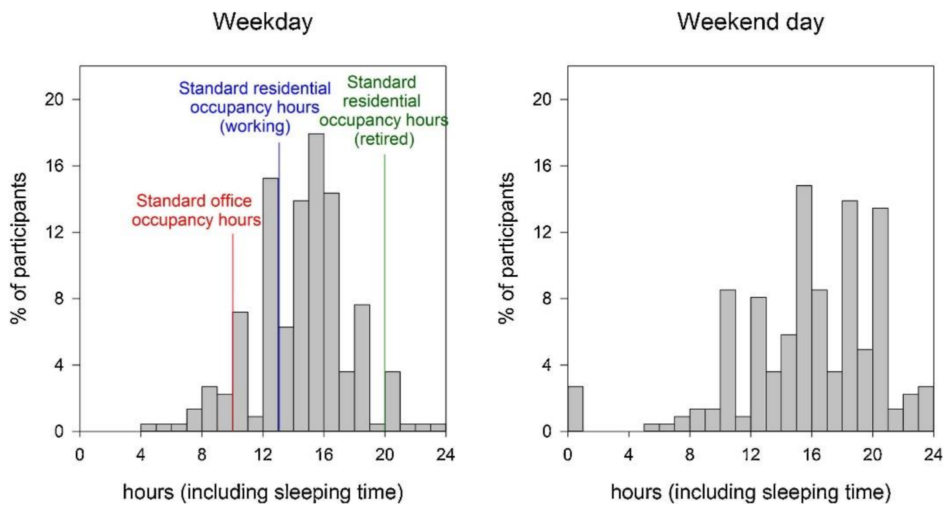

Fig. 5. Histogram showing reported number of hours spent in the bedroom (including sleeping time) by residents of Mayflower halls of residence complex during a typical weekday (left) and weekend (right) day. Also shown are some benchmark values for number of occupancy hours [37] for office buildings (red) and for two typical residential scenarios, working (blue) and retired occupants (green) [32]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Responses to questions on the frequency of use of indoor environmental controls, specifically use of heater, window opening and use of curtains show diversity in the reported behaviour of occupants (Fig. 6). Use of the heater shows a relatively even spread across the categories with a majority reporting using the heating controls less than once per month ("never"); this does not, however, specify the setting the heater is left at for most of the time. Respondents demonstrated a high rate of window opening and curtain use with 76% and 77% respectively reporting using these controls either daily ("often") or more than once a day ("frequently"). As with use of heating controls, it is not specified whether those reporting opening windows or curtains less than once per month have these controls open or closed for the majority of the time. However, infra-red imaging indicates that a significant percentage of windows are in the open state during the heating season as shown in Fig. 2.

When the use of controls are considered by gender, male participants reported using both windows and curtains more than once a day ("frequently") significantly more than female respondents. In the case of curtain use, this was 47% for males and 33% for females and for windows, 50% for males and 37% for females. In both cases, females have a higher representation for the next category representing use of these control daily ("often"). By contrast, male respondents report using their heating controls less than once per month ("never") more than female respondents (40% and 25% respectively) with female respondents carrying a higher percentage in categories representing more frequent use of heating controls. However, these differences, shown in Fig. 6, are small and could imply that factors other than gender play a more significant role in determining behaviour with respect to indoor environmental controls e.g. familiarity with type of heating system or control regime in previous residence.

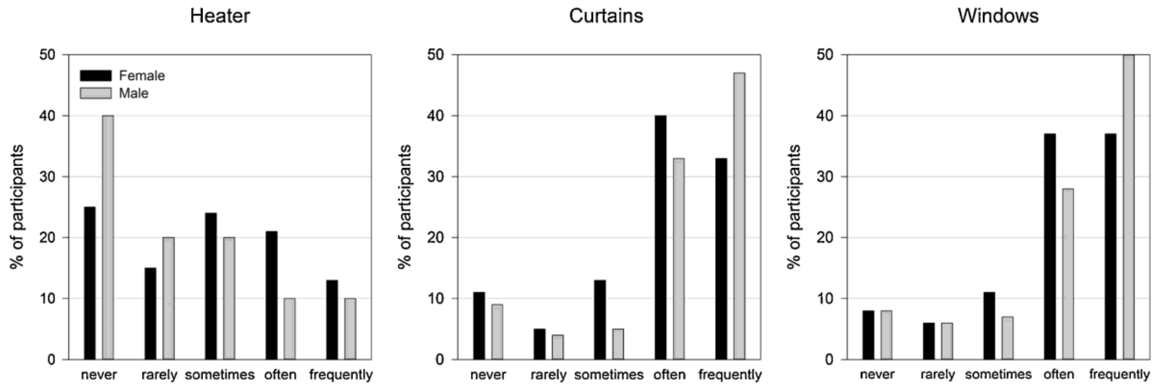

Fig. 6. Occupants' reported use of indoor environmental controls for heating, curtains and window opening classified by gender where "never" is less than once per month, "rarely" is once per week, "sometimes" is 1–2 times per week, "often" is daily and "frequently" is more than once per day.

Finally, the use of controls were examined with respect to previously experienced climate; a description of how the participants were grouped into Category A (cold/cool) and Category B (warm/hot climates) is given in Section 2.1. Since there were significantly more responses from Category A climates (174) than Category B climates (46), the use of indoor environmental controls are considered by percentage rather than absolute number (Fig. 7); 3 participants did not state the location of their previous residence. It is observed that those from Category A climates report higher use of curtains and windows with higher percentages reporting 'frequently' and lower use of heating controls ('rarely' and 'never').

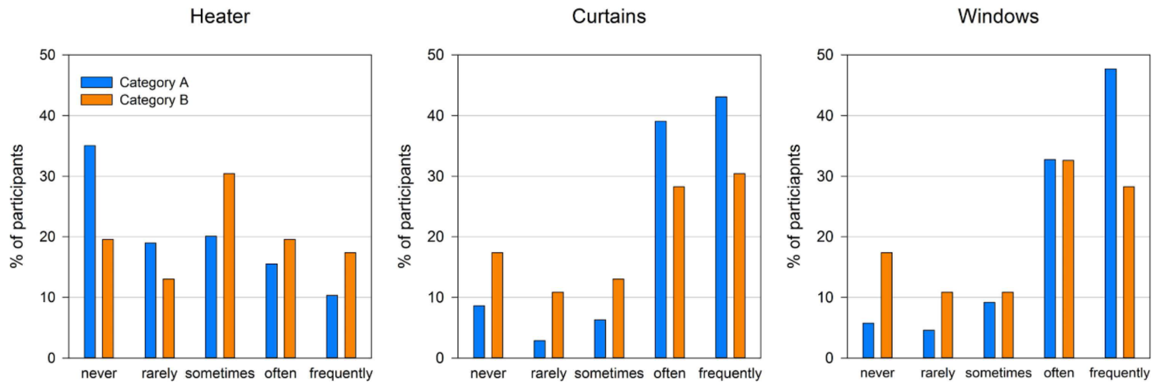

Fig. 7. Occupants' reported use of indoor environmental controls for heating, curtains and window opening classified by climate prior to moving to the case study building where "never" is less than once per month, "rarely" is once per week, "sometimes" is 1–2 times per week, "often" is daily and "frequently" is more than once per day. Category A refers to "cool/cold" climates and Category B to "warm/hot" climates.

To understand how use of indoor environmental controls affects overall satisfaction with the indoor environment, the use of controls is shown along with responses regarding how occupants describe the temperature in their rooms during the winter. The majority (56%) of the residents feel that the temperature is satisfactory or 'ok' and there are more residents reported being 'too warm' (8%) than 'too cold' (2%). Responses indicating slightly 'too warm' or 'too cold' are similar in number at 18% and 15% respectively. Considering heater use, it is interesting to note that those who report being satisfied with the indoor temperature in their bedroom are the dominant group across all categories of heater use. This implies the importance of end user control of the indoor environment to achieve satisfaction and comfort. Furthermore, those that report feeling 'too warm' or 'a bit too warm' are strongly represented in the category of 'never' using the heater and 'frequently' using the windows. This implies adaptive comfort behaviours, despite residents not being entirely satisfied with the resulting temperature conditions. However it is unclear at this stage whether or not these adaptations can be said to be effective since the circumstances under which each type of action is taken is not stated.

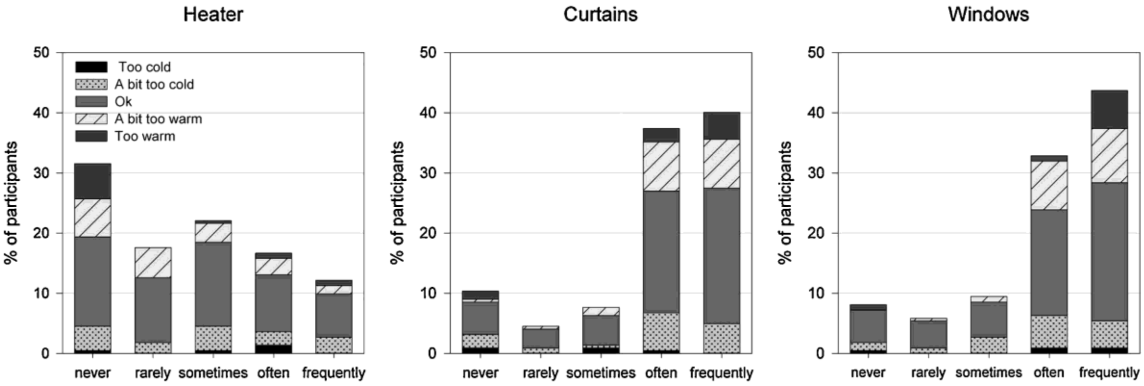

Fig. 8. Stacked bar chart showing occupant's reported use of indoor environmental controls categorised by occupants' general description of indoor temperature during the winter (223 respondents). "Never" is less than once per month, "rarely" is once per week, "sometimes" is 1–2 times per week, "often" is daily and "frequently" is more than once per day.

Part 2–Environmental Monitoring and Thermal Comfort Surveys

Monitored data of temperature and relative humidity at 5 min intervals was collected from December 2014 to May 2015 in 30 rooms of Mayflower Halls alongside the same questionnaire used in Section 3.1 relating to use of indoor environmental controls. The results showed average indoor temperatures varying from 19 ◦C to 29 ◦C, with minimum and maximum temperatures reaching 12.4 ◦C and 32.9 ◦C respectively. Since a certain degree of variation is expected over the year due to seasonal weather changes, a shorter period of time, the month of February 2015, was considered. This month was selected as it is during the heating season and academic term time so the student residents would be occupying the buildings. The mean outdoor temperature for this period was 4.1 ◦C in the South of England, which is 0.4 ◦C lower than the long term (1981–2010) average for this month [32]. It was observed that mean indoor temperature ranged from 19 ◦C to 32 ◦C, where the standard deviation (u) of these means is 2.4. Fig. 9 shows the air temperature distribution of these 30 rooms for February 2015, where the box plots represent the 10th, 25th, 75th, 90th percentiles and median, the red line represents the mean and the outliers are shown by the grey circles. Since occupancy was not monitored in this instance, the data presented in Fig. 9 is of all recorded temperatures for the month of February. It can be seen that while the majority of the samples presented here have mean values that lie within the recommended indoor temperature range for heating, taken from EN 15251 [11], they all have values outside this range as depicted by the grey circles. This has implications for the design process since it is likely that mean values of indoor temperature are used in energy models and it is evident that these may not lead to acceptable indoor temperatures at all times, which could lead to negative feedback at the POE stage, depending on frequency of occurrence. Interestingly, as seen in Fig. 8, students' general feedback on their room's temperature is positive, which means that the range of room temperatures for this diverse population is acceptable overall. This is perhaps a reflection of the 'bundled' charging mechanism for rent and heating resulting in residents being able to use windows or heating controls without financial penalty.

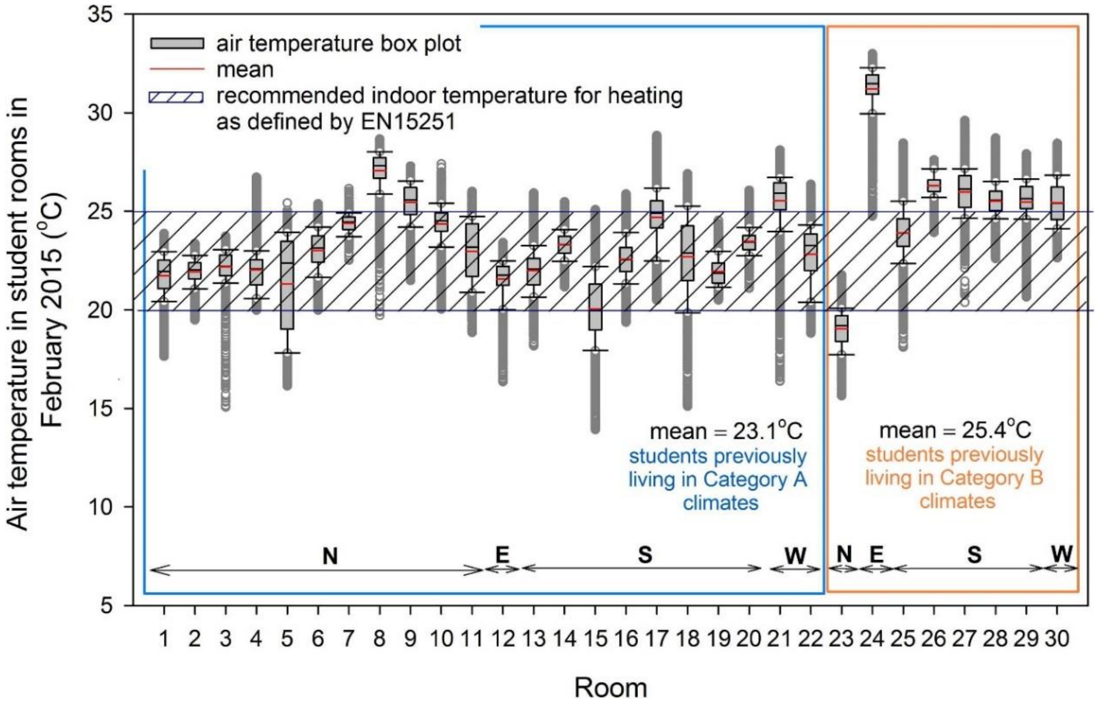

Fig. 9. Boxplot of air temperature in 30 monitored rooms of Mayflower Halls of residence for February 2015 where the 10th, 25th, 75th, 90th percentiles and median are shown in the boxplot. The red line represents the mean and outliers (below 10th or above 90th percentile) are shown as the grey circles; students previously living in Category A (cool/cold) climates are shown in the blue box and Category B (warm/hot) climates are shown in the orange box. The rooms are grouped by facade orientation: North (N), South (S), East (E) and West (W) shown by the arrows. The shaded area represents the recommended indoor temperature for energy calculations taken from EN 15251:2007 [11]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Considering the orientations of the rooms, which could influence the indoor air temperature, it was found that in the Category A group, the average temperature for February 2015 for north facing rooms was 23.3 ◦C compared to 22.6 ◦C in South facing rooms. For the purpose of this study, north facing rooms include north-west and north-east and south facing rooms include south- west and south-east as north-south orientation will have the most significance during the winter. If room orientation was strongly influencing indoor room temperature we would expect that the south facing rooms would have a significantly higher temperature, than the north facing. Instead, we see the north facing rooms displaying higher temperature though the difference cannot be said to be significant. This implies that room orientation may not be the most influential factor in determining room temperature during the heating season where it is likely that all rooms will require additional heating to maintain a comfortable temperature. However, further research is needed to confirm this as the room sample size employed here is small.

The participants were also asked to rank their overall perception of the temperature conditions in their bedroom during the winter where the response options were: Too cold (−2), A bit too cold (−1), Ok (0), A bit too warm (1) or Too warm (2). It is interesting to note that the average for the participants from Category A climates was 0.2, indicating that on average, these residents feel slightly warm and for the Category B participants, the average was −0.4 which implies that despite having a higher average indoor temperature, residents from warmer climates still report feeling slightly cool in the building. These responses are plotted against the rooms' mean indoor temperature in Fig. 10.

Considering then the cases where the mean indoor temperature value lies above the recommended range (20–25 ◦C), it is interesting that only one participant (Room 27) answered "Too hot" when asked to describe the indoor temperature during the winter. Perhaps more notable however, is that 3 of the 6 Category B participants (Rooms 24, 28 and 29) whose mean temperature is above the recommended range all reported being either too cold or a bit too cold despite having average temperatures over 25 ◦C, with one (Room 24) having an extremely high average of 31 ◦C. By contrast, the three participants from Category A climates whose mean values were above the recommended range all responded 'Ok' when asked about the temperature conditions in their rooms. This implies that while on paper, these indoor temperature would be considered unacceptably high, in this instance, they are satisfactory for the occupant. In Fig. 10, an additional category has been added to the data set which highlights the occupants from cool, non-UK climates; these are represented by the blue squares. It can be seen that there is only one resident from the UK whose living space is on average outside the EN 15251 recommended indoor temperature range for heating (20–25 ◦C) [11].

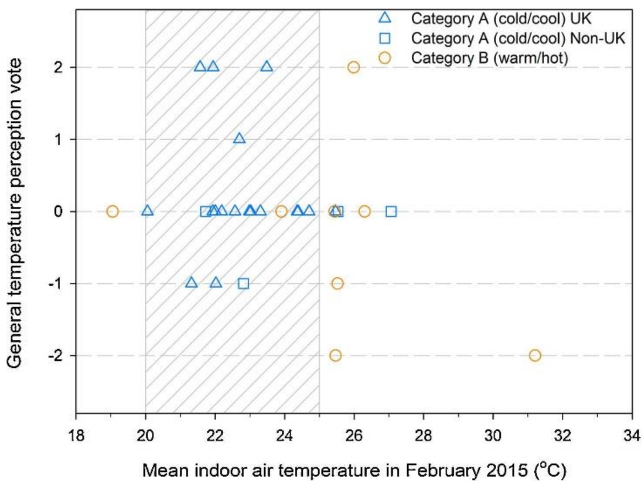

Fig. 10. Plot of overall temperature perception vote for the winter against mean indoor temperature for February 2015 where −2 is "too cold", -1 is "a bit too cold", 0 is "ok", 1 is "abit too warm" and 2 is "too warm" on the y axis.

As highlighted earlier, the monitoring data presented here includes all recorded values for the month of February 2015, not specifically occupied times. It is therefore possible that these monitored temperatures do not necessarily reflect participants' preferred temperatures. For example, radiators left on or windows left open while residents are not occupying their room could result in temperatures being higher or lower than preferred temperatures. Fig. 11 shows the comfort temperature calculated using the Griffiths method against the mean monitored temperature for February 2015 of the 30 accommodation rooms coloured by climate of previous residence. The regression line of all data points shows that the comfort temperature is correlated to the mean monitored temperature in February ($r = 0.65$, $p = 0.0001$) with $T_{com} = aT_{mon} + b$. Therefore, the mean monitored temperature can be taken to closely represent overall thermal preference.

As can be seen in Fig. 11, respondents' comfort temperatures ranged between 19 ◦C and 28 ◦C, in close agreement with the range in mean monitored room temperatures in February (19–31 ◦C). Thus, it seems that the diversity in temperature preference may not be sufficiently well catered for in the case study building given that many residents have expectations and adaptations that are significantly different than those accounted for in the relevant building standards. This will affect the buildings energy performance thereby highlighting user driven performance gap in a halls of residence context.

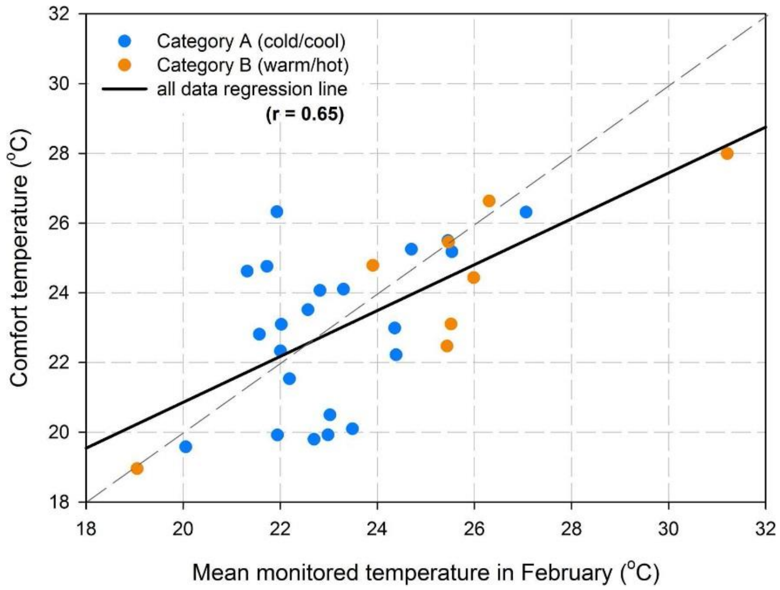

Fig. 11. Comfort temperature calculated using the Griffiths method plotted against mean monitored indoor air temperature in February 2015 of 30 accommodation rooms of Mayflower halls. The solid black line shows the regression line using all data points.

4. Conclusion

In this paper, results from on an online POE study of a newly built halls of residence complex were used to examine the level of diversity in how occupants use the indoor environmental controls available to them. Whilst it is likely that some of this variation is due to differences in the conditions in the rooms due to orientation and floor level, it is inferred from this study that there are other influencing factors at play. Some of these, such as level of proactivity in addressing thermal discomfort which is largely a personality trait, are hard to address and impossible to predict. However, differences observed in use of controls by occupants from Category B (warm) climates indicate that there are factors relating to long term thermal history, previous experience of indoor environments and perhaps cultural practices that are driving behaviour. While this initial study does not draw any generalisations, should it be more fully understood, this type of parameter has the potential to be included in the design process either as an input at the design stage or as part of a post occupancy, 'Soft Landings' approach [33].

The second part of this study used monitored air temperature measurements for February 2015 along with questionnaire results and thermal comfort surveys to investigate variation in indoor temperatures in 30 rooms of the case study building complex. The average monitored air temperatures in the rooms were found to be correlated with comfort temperature which implies that they can be taken to be a reasonable indicator of overall preferred temperature. Mean air temperatures ranged from 19 ◦C to 31 ◦C with a standard deviation (u) of 2.4. Whilst indoor temperatures cannot be expected to be uniform throughout a building like this, where there are many influencing factors both in building design and occupant preferences, this large range is striking. The mean values of temperature are also noteworthy when considered with respect to the recommended indoor temperature range for heating (20–25 ◦C). It was found that almost all the mean values that lay above this range were of rooms where the occupant had, for the two years prior to living in the case study building, been living in a warm or hot climate. Furthermore, some of these occupants reported finding the temperature in their room was generally too cold (or a bit too cold). This difference in indoor temperature preference is even more evident when considering residents from cool non-UK climates. It is shown that all but one of the rooms that had a mean temperature outside the 20–25 ◦C range belonged to residents who have previously not been living in the UK. Furthermore, in this study, room orientation did not appear to be a factor in determining winter season indoor room temperature.

While the sample sizes presented here are too small to form generalisations they are comparable to other comfort studies conducted in similar residential contexts [34,35,36]. The findings present an interesting question of whether or not buildings designed for UK standards are able to meet the comfort needs of international residents and moreover how this can be addressed in the future. It is also expected that over time, residents from differing climates are likely to adapt to the thermal conditions in their new environment. However, since this study has only considered one month in the year (February 2015) and the residents would all have moved in four months prior (October 2014), it is not possible to say how much (if at all) of this adaptation has taken place. Further work will need to be carried out in the earlier months of residents' occupancy in order to investigate this lag in adaptation time. This is of particular interest in this case due to the unique nature of the building where, for the most part, there is a new set of occupants each year. This adaptation time lag could have significant implications for overall energy performance.

Further research is necessary to understand how best to address the issues of varying preferences and behaviour based on climate history. This work raises some interesting questions on how best to develop inclusive management and design strategies to account for significantly different indoor temperature preferences. For example, in situations where it is expected that there will be residents with diverse climate histories (as in the case study used in this paper) it is possible to design specifically for multiple indoor climates. This would create a zoned system where different areas could provide comfortable living conditions for residents with varying thermal preferences. Alternatively, in cases of existing buildings, a management strategy could be developed to profile residents based on climate history before arrival and locate them in rooms that are likely to match their existing preferences. This could include, for example, placing a resident who is expected to have a preference for higher temperatures in a sheltered high floor level south facing room to optimise both solar gain and stratification effects. This would also allow rooms that are likely to be cooler to be occupied by residents who have a preference for lower indoor temperatures. This strategy would also reduce summer overheating risk as occupants with higher winter temperature preference are likely to tolerate higher summer temperatures. This could present a simple solution to improving comfort by optimising the characteristics of the building to suit the specific needs of the occupants.

Acknowledgements

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II – Future Cities & Environment journal paper

Revised version

Exploring the link between thermal experience and adaptation to a new climate

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Abstract

Numerous field studies conducted in different locations have found that peoples' thermal comfort varies with local climate. However, little is understood about the effect of moving from one climate to another. Literature suggests that people would be able to adapt to the typical indoor climate in a new location, though estimated timescales for this process differ. This paper uses data from a 6-month field study to investigate the process of thermal adaptation to a new climate. The field study consisted of a series of four thermal comfort surveys conducted with 48 occupants of single occupancy residential accommodation units, which helped to estimate their preferred temperatures. The surveys were carried out between October 2015 and April 2016 with high resolution indoor air temperature data collected for the periods between the surveys.

Study participants were grouped into three categories: long term residents of the UK (Category A), recently moved to the UK from cold climates (Category An) and recently moved to the UK from warm climates (Category B). The higher indoor temperatures of participants from cool climates (Category An) indicates the influence of indoor thermal history in determining thermal comfort conditions in a new location. This is highlighted by the fact that 94% of Category An participants reported having heating in their previous residence compared to 17% of Category B participants. Analysis of comfort temperatures over the first 6 months of occupancy shows no indication that occupants from Category An or B are adapting their indoor preferences to match that of long term UK residents, given the choice to create their preferred environment. Finally, comparison of indoor air temperature and comfort temperature found a higher correlation in Category A participants which supports the key principles of adaptive comfort theory. Category An demonstrated fairly close correlation though air temperatures were higher than comfort temperatures which may be due to embedded heater use behaviour patterns. Category B demonstrated no correlation between comfort temperature and air temperature which may be due to unfamiliarity to indoor heating systems.

Keywords: adaptive thermal comfort, indoor temperature, occupant behaviour, thermal history, comfort temperature, heating

1. Introduction

Many field studies have been conducted in various climates across the world which demonstrate that comfort temperature is closely linked to local climate (Brager & de Dear 1998; McCartney & Nicol 2002; Nicol 2017; Taleghani et al. 2013; Zhang et al. 2017). Adaptive thermal comfort theory explains this phenomenon with respect to occupants' active engagement with their indoor environment (de Dear & Brager 1998; Nicol et al. 2012). This is to say that if an environment causes an occupant discomfort, they are likely to take responsive actions to restore comfort (Nicol & Humphreys 2002). These responsive actions are said to be rooted in one of three types of adaptation: behavioural, physiological or psychological (Brager & de Dear 1998). Conceptually, all three can be linked to local climate in some way however these relationships have not been studied rigorously (Schweiker et al. 2012).

Despite the fact that adaptation is a fundamental aspect of adaptive thermal comfort theory, little research has addressed the nature of adaptation or the influence of thermal history on current preferences. The majority of the studies addressing thermal history have been conducted by Luo et al. in China and employ groups of participants moving between Northern and Southern China (Luo, Ji, et al. 2016; Luo, Zhou, et al. 2016; Luo, de Dear, et al. 2016). A key factor in these studies is the availability of district heating in northern regions where the climate is described as 'severe cold' (Luo, de Dear, et al. 2016). In contrast, southern regions are not provided with district heating despite cold winter temperatures. The key findings from this group of chamber and field studies are firstly that occupants adapt more easily to neutral conditions than more severe conditions (Luo, de Dear, et al. 2016). Secondly, these studies find that in addition to local climate, indoor thermal history influences thermal adaptation (Luo, Ji, et al. 2016; Luo, de Dear, et al. 2016). This is also supported by findings from a climate chamber study which investigated differences in thermal preferences between participants from Nigeria, Turkey and Hungary (Kalmár 2016).

This study aims to compare the thermal preferences and adaptation of occupants from different climate zones after they moved to a new location. Further to this, presented here is an investigation into the relationship between thermal experience and change of thermal preferences in a modern residential building taking into account seasonal variation in local weather conditions.

2. Study Design

Field studies of thermal comfort typically involve structured subjective responses to indoor conditions (ISO 2005; ASHRAE 2013) alongside measurements of the environment using a sensing station (ISO 2001). Increasingly, studies are also employing air temperature and humidity monitoring devices for longer term assessment of the indoor environment. The Griffith's method is a commonly used method for determining the comfort temperature of participants in studies with relatively small sample sizes (Griffiths 1990; Nicol et al. 2012). This simple method linearly adjusts the operative temperature (Top) based on participants vote (TSV) on the seven point ASHRAE thermal sensation scale (ASHRAE 2013) to give a comfort temperature (Tcom) (Griffiths 1990; Nicol et al. 2012):

$$Tcom = Top - TSV/0.5$$

In order to investigate the link between thermal experience and adaptation to a new climate, a mixed methods field study was developed. The field study was conducted in the University of Southampton's Mayflower halls of residence complex (Section 2.1). Convenience sampling was used which resulted in a total of 47 participants. The study includes an in-depth participant questionnaire, a series of four thermal comfort surveys and long term, high resolution indoor temperature monitoring conducted during the academic year commencing in 2015. A timeline for the surveys is shown in Table 1. The first questionnaire, conducted within a month of the start of the occupancy period, included details of participants' background such as location (city and country) of previous residence and availability of heating and cooling in previous residence. The thermal comfort survey, conducted with the initial survey and a subsequent 3 times, was based on the questionnaire used in the SCATs database (McCartney & Nicol 2002). Notably, this included thermal sensation on a 7 point ASHRAE scale (ASHRAE 2013).

All face to face surveys were conducted in participants' accommodation rooms and were accompanied by measurements of the indoor environment (air temperature, radiant temperature, air velocity and relative humidity). These were taken using the ISO 7726 (2001) compliant DeltaOhm HD32.3 portable sensing station. These measurements, along with the subjective thermal sensation responses allowed for the calculation of comfort temperature using the Griffiths method as described in the Introduction. During the first survey visit, an air temperature and humidity data logger (MadgeTech RH101A) was installed in each participants' room. The logger was placed in one of two locations chosen to ensure no direct solar radiation or heat source and was set to record single measurements of the air temperature at 5 minute intervals. For the purpose of this investigation, three 1 week monitoring periods between surveys were selected (Table 1). Selection of the time period was based on equidistance from surveys either side while also avoiding university holiday periods where occupants were likely to be away. Figure 1 provides a timeline showing the month of the comfort surveys and the selected monitoring periods.

Table 1 Study details and timeline with mean ambient outdoor temperature (weatherunderground 2016)

Month	Type	Start date	End date	Average monthly ambient temperature (^oC)
October	Comfort survey + background	19/10/15	03/12/15	11.2

November	Monitoring	16/11/15	22/11/15	10.3
December	Comfort survey	30/11/15	14/12/15	10.6
January	Monitoring	11/01/16	17/01/16	5.8
February	Comfort survey	02/02/16	11/02/16	5.4
March	Monitoring	07/03/16	13/03/16	6.3
April	Comfort survey	18/04/16	27/04/16	8.5

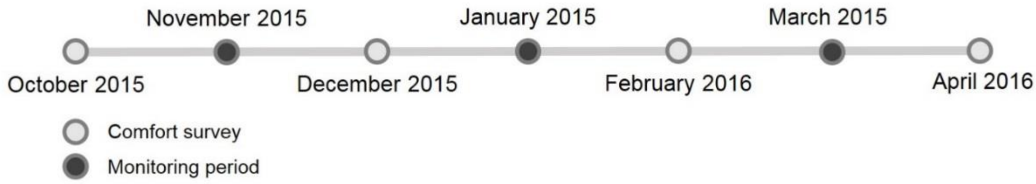

Figure 1 Study timeline showing comfort surveys and monitoring periods

Participants were grouped into three categories based on average winter temperatures in the location of residence prior to occupancy in Mayflower. The categories are as follows:

Category	Description
A	Mostly living in the south of the UK for the two years prior to moving to Mayflower
An	Mostly living in a climate with winters as cold as or colder than Southampton for the two years prior to moving to Mayflower
B	Mostly living in a climate with winters warmer than Southampton for the two years prior to moving to Mayflower

2.1. Case Study: Mayflower halls of residence

The case study site is the University of Southampton's Mayflower halls of residence which is located in Southampton city centre. Southampton is a port city on the south coast of England, 75 km south-west of London, with a Köppen-Geiger classification of Cfb. The complex, comprised of three buildings, provides over 1000 accommodations rooms. These are mostly arranged in cluster flats with shared kitchen/living spaces though some studio and one-bedroom flats are also available. The location and layout of the complex is shown in Figure 2. Each room has top opening tilt windows (with trickle vent) and radiator with thermostatic radiator valve to facilitate personal control of the indoor environment. This was selected as suitable case study as the similarity in design of the accommodation units make comparison between occupants straightforward by eliminating variation in building construction factors which are key determinants of indoor environment. Furthermore, the high number of international students studying at the University of Southampton ensured a sampling frame with diverse thermal histories.

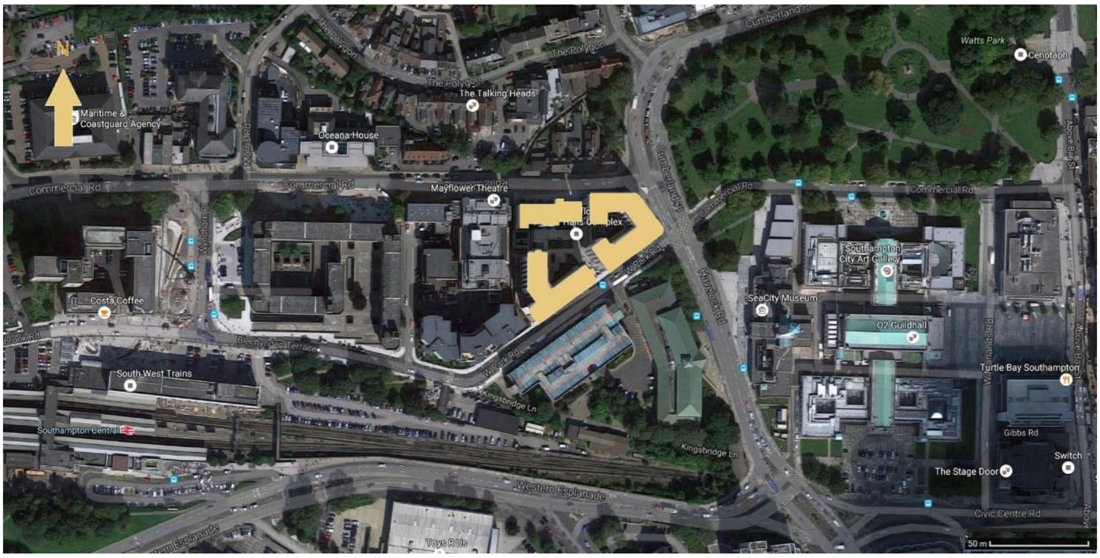

Figure 2 Map showing location and schematic outline of Mayflower halls of residence complex

3. Results & Discussion

The study resulted in 47 complete data sets (N=47) with Category A, An and B comprised of 17, 18 and 12 participants, respectively. Presented in this section are summary results of the indoor air temperatures and comfort temperatures. Also discussed here is a comparison of these two indicators of thermal preference.

3.1. Indoor temperature monitoring

Figure 3 presents box plots of monitored indoor air temperature for each of the three selected periods grouped by climate of previous residence. Also shown is the design indoor temperature range as given by the EN15251 standard (CEN 2007). Both Categories A and B have group mean air temperatures within the recommended range whereas the Category An group means lie above this range. Category An was found to be significantly higher than Category A in November by 2.1oC and higher than Categories A and B in January, as shown in Table 2. The roman numerals represent statistically significant differences in comfort temperature determined by one way ANOVA (with Tukey's HSD post-hoc test). Due to non-normality of the data, as determined by Shapiro-Wilk test, ANOVA analysis could not be performed for the March data. The fact that Category An group means are above the design indoor temperature range provides further indication that European standards may not be providing comfortable indoor conditions for some residents, due to their different preferences (Amin et al. 2016).

The background survey revealed that 94% of Category An residents had indoor space heating in their previous residence, compared to 17% of Category B residents. Furthermore, 76% of those Category An are from China where regulation stipulates that areas in the Northern region where severe winters are typical must have government controlled district heating. It is common in these regions for homes to have no heating controls and high indoor temperatures (Cao et al. 2014; Wang et al. 2017).Therefore it is possible that many Category An residents are using their heating controls in this manner, resulting in high, but perhaps comfortable, temperature conditions. This points to the importance of behavioural and psychological adaptation in a new climate context.

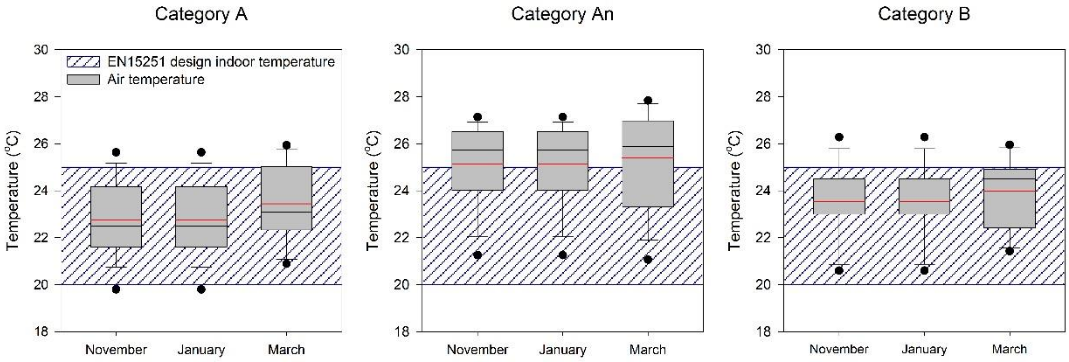

Figure 3 Monitored indoor air temperature for the three selected periods grouped by climate of previous residence

Table 2 Mean and standard deviation of indoor air temperature grouped by climate of previous residence

	Indoor air temperature T_a (°C)					
	November		January		March	
	mean	σ	mean	σ	mean	σ
Category A	22.6^{i}	1.3	22.7^{ii}	1.6	23.4	1.6
Category An	24.7^{i}	1.4	25.1$^{ii, iii}$	1.7	25.4	2.0
Category B	23.7	1.2	23.5^{iii}	1.5	24.0	1.4

$^{i, ii, iii}$ indicates statistically significant difference between groups

Figure 3 also demonstrates that there is little change in indoor temperature in the rooms from one period to the next. This is also highlighted in Figure 4, which shows the hourly averaged indoor air temperature for each room for the three selected periods. Again, this is grouped by climate of previous residence (shown in colour) with the daily mean outdoor temperature included for reference (SOTONMET 2017). For all categories this is notable since it provides no indication of seasonal variability. The stable and high temperatures from November to March indicate that as a group the residents who are new to the UK, Categories An and B, are continuing to maintain their higher preferred temperatures rather than adapting to match the preferences of the long term residents. This calls into question the utility of passive climate chamber studies investigating adaptation times to new climates as they overlook the interaction of occupants with controls and the building. While it may be possible for people to adapt to new indoor conditions, if they are able to modify their environment they may instead continue to match their environment to their preferences over the long term.

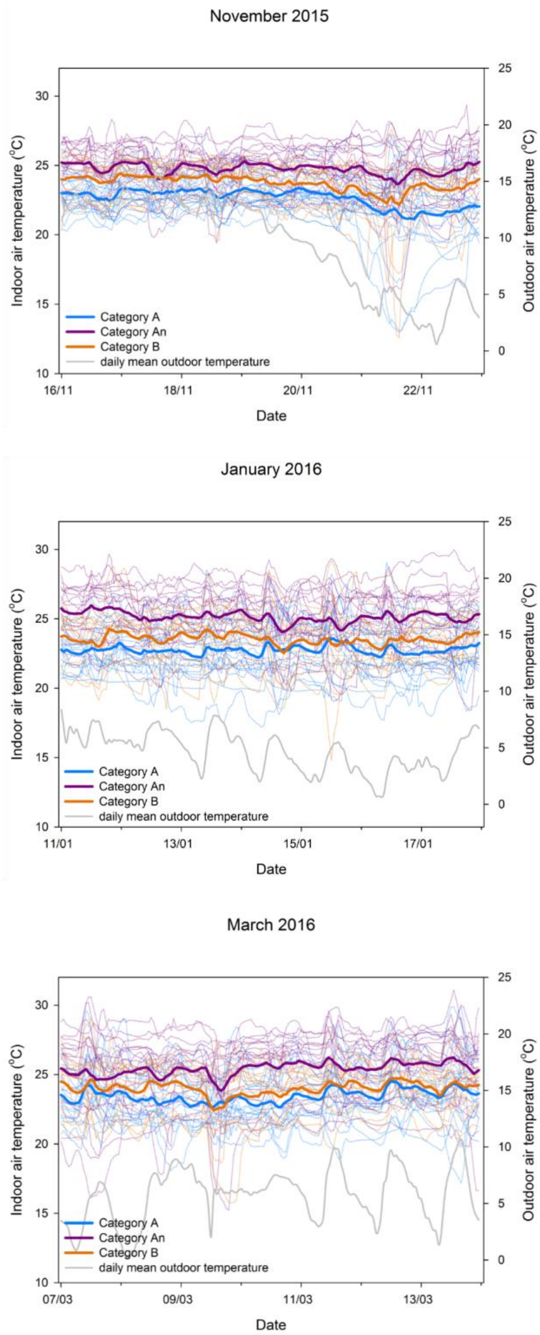

Figure 4 Hourly averaged indoor air temperature (left axis) for each accommodation unit for three one-week periods grouped by climate of previous residence. The hourly averaged ambient temperature is shown on the right axis.

3.2. Comfort temperatures

Figure 5 shows the distribution of comfort temperatures, calculated using the Griffiths method grouped by climate of previous residence. These results are also summarised in Table 3. The roman numerals represent statistically significant differences in comfort temperature determined by one way ANOVA (with Tukey's HSD post-hoc test). Category B is found to have a significantly higher mean comfort temperature than Category A in the first (1.7oC) and second (2.2oC) survey conducted in October and December, respectively. Due to non-normality of the data, ANOVA analysis could not be performed on the February or April surveys. On average, the comfort temperatures of Category A subjects were lower than the other two groups and well within EN15251 design values. While the comfort temperatures fluctuate slightly over time, there are no significant differences between surveys in any group.

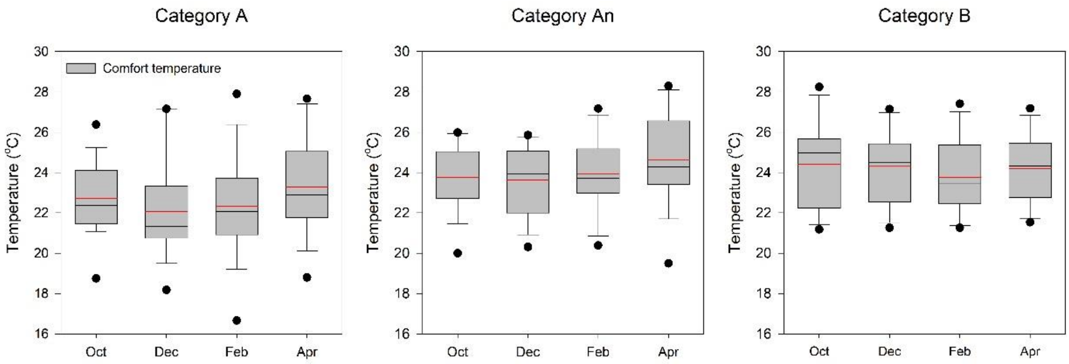

Figure 5 Comfort temperature for each survey grouped by climate of previous residence

Table 3 Comfort temperatures calculated using the Griffiths method grouped by climate of previous residence

	Comfort temperature T_{com} (°C)							
	October		**December**		**February**		**April**	
	mean	**σ**	**mean**	**σ**	**mean**	**σ**	**mean**	**σ**
Category A	22.7[i]	1.8	22.1[ii]	2.4	22.3	2.6	23.3	2.4
Category An	23.8	1.6	23.6	1.7	23.9	1.8	24.6	2.2
Category B	24.4[i]	2.2	24.3[ii]	1.8	23.8	1.9	24.4	1.7

[i, ii] indicates statistically significant difference between groups

3.3. Comparison of preferred and actual temperature

Based on the principle of adaptive thermal comfort, it is expected that indoor air temperature is closely related to comfort temperature. This assumes that individuals take appropriate actions (e.g. opening windows, turning on radiators) to maintain comfort. Figure 6 shows the relationship between mean indoor air temperature across the three selected monitoring periods and mean comfort temperature across all four surveys. The grey reference line corresponds to the case of 'perfect' adaptation, where the indoor temperature equals the occupant's comfort temperature. There is a significant correlation (r = 0.58) between the two values when considering the whole data set (not considering climate category) which supports the assumption of the adaptive principle. Category A, long term UK residents showed the highest level of correlation (r=0.65) with Category An also demonstrating reasonably close correlation (0.55). Category B, however, showed very weak correlation (r=0.28). This indicates that they are the least able to maintain comfortable conditions.

A higher degree of correlation in Category A supports a key premise of adaptive comfort theory as it indicates that those most accustomed to the local conditions, climatic and cultural, are best able to achieve comfort. Many of the Category An participants have air temperatures higher than their comfort temperature. This provides further evidence that heating controls are being used in a similar way to the district heating systems of their home country which in this context is compromising thermal comfort. Weak correlation between comfort temperature and air temperature in Category B may be due to a lack of familiarity with the new conditions they experience, especially indoor heating systems, with only 17% having had heating in their previous residence.

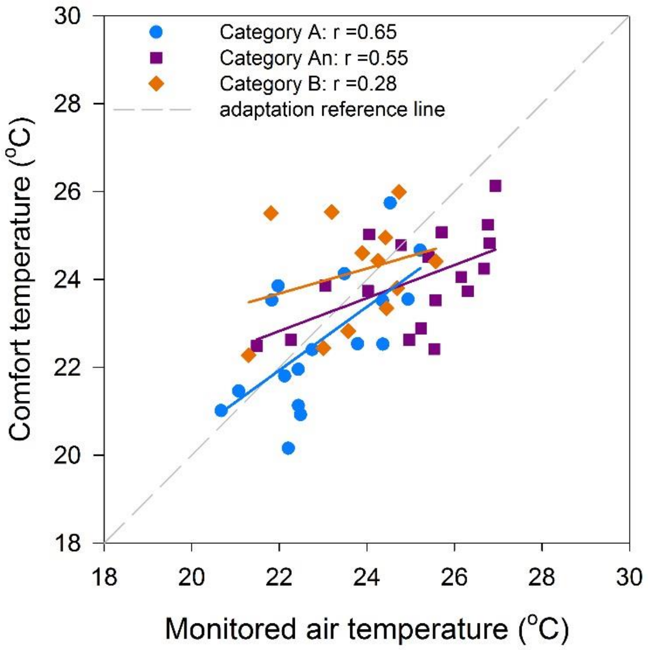

Figure 6 Relationship between participant's mean comfort temperature across the four surveys and mean indoor air temperature for the three monitoring periods. The correlation coefficient (r) for the whole data set is 0.58.

4. Conclusions

This paper presented results from a 6-month field study investigating the relationship between thermal experience and adaptation to a new climate. There were significant differences found in indoor air temperature between climate categories in 2 out of the 3 monitoring periods, with long term UK residents' (Category A) being lower in both instances. Participants from cold climates not including the UK (Category An) had consistently high indoor air temperatures which is likely to be due to being accustomed to high levels of central space heating. This highlights the importance of indoor climate experience in determining long term thermal preference and behaviour. Category B (warm climates) participants were found to have a higher mean comfort temperature than Category A in 2 out of the 4 thermal comfort surveys. Additionally, neither the Category An or B groups changed comfort temperature from one survey to the next indicating that no significant adaptation to the new climate took place during the investigated period of 6 months. This shows that, unlike acclimation climate chamber experiments, where acclimation may take place within 1-2 weeks (van der Lans et al. 2013;

Pallubinsky et al. 2017), in real environments the duration of adaptation appears to be much longer.

Comparison of indoor air temperature and comfort temperature demonstrated that Category A had the highest level of correlation (r = 0.65). This supports the principles of adaptive thermal comfort in that those most accustomed to the environment, are most able to achieve comfort. Category An participants had reasonably high correlation (r=0.55) but with higher indoor air temperatures compared to comfort temperatures which may be explained by space heating provision with limited individual control in their previous residence. Category B participants showed very weak correlation between comfort temperature and air temperature, indicating that this group were least able to control their environment to suit their preferences.

The findings of this study are likely to have implications for the energy use of buildings of this type since space heating is used in unexpected ways. However, it also presents opportunities for easing the transition to a new indoor environment for occupants. In particular, it is clear that occupants from warm climates, typically unfamiliar with space heating, would benefit from guidance on the heating controls. This is also true of some participants from cold climates who may be accustomed to space heating but not controls at the individual level. The relationship between comfort temperature and air temperature requires further investigation since the direction of causation is unclear. Either way, this could be used in aiding the transition to a new climate. This could be by helping occupants to match their comfort temperature to typical indoor environments in their new setting or by adjusting the design, operation and management of the building to provide them with their most familiar conditions. An example of this could be to place occupants who are expected to have higher comfort temperatures on the facades of a building which receive the highest solar gain.

5. Acknowledgements

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II – Windsor 2016 conference paper

Investigating the impact of thermal history on indoor environmental preferences in a modern halls of residence complex

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Abstract

Numerous field studies conducted in different locations have demonstrated that comfort conditions vary due to adaptation to the local climate. This study aims to investigate how preferences for the indoor environment change when the climate context changes and how thermal history influences comfort conditions in a new thermal environment. A new halls of residence complex in the south of England, housing occupants from various climatic regions, is used as a case study. Two thermal comfort surveys were conducted in October and December 2015 (N=53 residents) within the first three months of the occupants. Air temperature and relative humidity measurements were collected during this period.

Results show a range of comfort temperatures of over 10°C across the study period. The first survey (October) found no significant difference between residents when grouped by previous climate of residence. The second survey (December) found that the mean comfort temperature for residents from the UK had dropped by 1°C, despite an unseasonably warm winter, and mean comfort temperatures for residents from other climates remained the same. This could be an indication of psychological adaptation whereby residents accustomed to the UK climate expect cooler temperatures moving from October to December and thus come to prefer this.

1 Introduction

With increasing focus on reducing carbon emissions to mitigate climate change impacts and meet the UK's 2050 emissions reduction target of 80% of the 1990 level (Climate Change Act 2008), energy efficiency measures are being addressed in a number of sectors. In the UK, domestic space heating alone accounted for 23% of total energy demand in 2011 (DECC 2013). While the technology to build highly efficient, low energy homes already exists, the challenge for designers is to provide functional and comfortable dwellings while maintaining low energy use. The difficulty lies in characterising occupant behaviour in the design stage which has been found to impact significantly on energy performance (Bonte et al. 2014; Gill et al. 2010; Martinaitis et al. 2015) and occupant satisfaction (Grandclément et al. 2014).

At present, occupants are usually assumed to be a homogenous population with similar thermal preferences. The recommended design temperature ranges in regulations and standards are based on studies carried out mainly in temperate climates (ISO 2005; CEN 2007). While this may be appropriate in the situation where all occupants under consideration are long term residents of the region, it becomes questionable when considering occupants from mixed climatic backgrounds. Many field studies have been conducted in various climates across the world which serve to demonstrate that comfort temperature is closely linked to local climate and to indoor temperature variation which is influenced by ventilation strategy (Rupp et al. 2015; Kwong et al. 2014; Taleghani et al. 2013; Brager & de Dear 1998). These studies have demonstrated that occupants of naturally ventilated buildings in hot climates can be comfortable at temperatures far higher than expected by deterministic models of comfort, sometimes exceeding 30°C (Djamila et al. 2013; Dhaka et al. 2013). Similarly, some studies have found the reverse, that occupants in cold climates can adapt to find comfort in low indoor temperatures (Ye et al. 2006; Yu et al. 2013; Luo, de Dear, et al. 2016).

Adaptive thermal comfort theory explains these variations in comfort temperature by asserting that over time, people are able to adapt to their climate through a combination of behavioural, physiological and psychological mechanisms (Nicol et al. 2012; de Dear & Brager 1998). Behavioural adaptation, linked to personal control, has been found to lead to diverse thermal preference (Brager et al. 2004; Luo, Cao, Zhou, et al. 2014) and in a number of cases this has been linked to energy performance implications both with respect to heating and cooling (Luo et al. 2015; Zhang et al. 2013; Zhang et al. 2010). Physiological adaptation or acclimatisation refers to changes in thermoregulatory mechanisms, such as sweating and vasodilation, which allow people accustomed to a particular climate to deal with exposure to that climate more effectively. While it is often considered to be less significant in explaining moderate changes in climate than behavioural and psychological adaptation (de Dear & Brager 1998), studies have suggested evidence for this (Lee et al. 2010; Yu et al. 2012). Finally, psychological adaptation is often hard to distinguish as a factor as the process and its impacts are hard to characterise. However, it has been postulated that expectations of how environments should be, based on experience, influences how people experience them (Humphreys & Nicol 1998)

This study aims to investigate how these adaptive processes change when considered in the context of a new climate. That is to say, the impact of individuals moving, with all their existing adaptations and thermal history developed in their 'home' climate, to a new climate where indoor environments are designed for residents with a different set of adaptations.

2 Methodology

This study employed a mixed methods approach utilising environmental monitoring, subjective questionnaires and data from a local weather station in a halls of residence complex. The case study is the University of Southampton's newly constructed Mayflower Halls of Residence located in the city centre of Southampton, UK. First occupied in October 2014, the complex provides 1104 naturally ventilated accommodation rooms most of which are single ensuite rooms arranged in cluster flats with shared kitchen/living room, although some studio and 1-bedroom flats are also available. This is considered a suitable case study as it houses a large number of international students who are likely to be of a similar age.

Figure 1 Mayflower Halls of residence facades. Top left: North-East facade, right: South-East facade, bottom left: courtyard and internal East and North West facades

Figure 3 shows schematic plans of typical accommodation units in Mayflower Halls. Each resident has access to controls enabling them to, in principle, maintain their indoor environment to suit their preferences. These include curtains, top opening tilt windows with trickle vents (Figure 4; left) and individual radiator valves with settings 0 to 5, where is 0 is off and 5 the highest setting Figure 2;right).

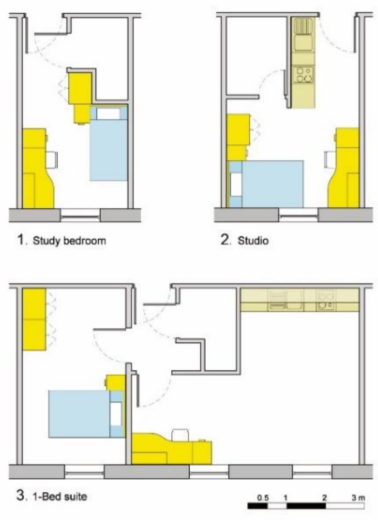

Figure 3 Schematic plans showing typical layout of accommodation rooms in Mayflower halls of residence

Figure 2 Indoor environmental controls available to Mayflower residents; radiator control valve (left), top opening tilt window with trickle vent (right)

2.1 Sample

Participation was open to all residents with first contact being made by email a few weeks after their one year occupancy began in the last week of September 2015. Since the focus of the study was to investigate the impact of thermal history, the intention was to have one third UK students and two thirds residents who had moved into Mayflower from another climate. Non-UK participants are those who stated that for the two years prior to moving to Mayflower, they had "…mostly been living in X…" where X was not the UK. The final sample employed for the study consisted of 56 residents, however this reduced to 53 later in the study period following three withdrawals.

In order to investigate differences in thermal preference between occupants already adapted to the UK climate and those who are not, a method to categorise climate history was introduced. Category A (cool/cold) climates are those where the mean temperature of the coldest month is equal to or lower than that of the coldest month in Southampton (4.6^{o}C); this group is further divided into UK and NON-UK in order to identify occupants from climates which may have colder winters than southern England. The mean temperature of Southampton was used (as opposed the UK) as temperature can vary quite significantly between the north and south of the country (965km) and since all the residents in the sample from the UK are from southern regions, Southampton was taken to be a representative location. Category B (warm/hot) climate are those where the mean temperature of the coldest month is higher than that of the coldest month in Southampton. This classification is used throughout the paper.

2. 2 Environmental monitoring

Air temperature and relative humidity were monitored in all participants' rooms starting in late October 2015 (a few weeks after residents had moved into the case study). This was done using MadgeTech RHTemp101A data loggers which provide measurement resolution of 0.01°C and 0.1% humidity for temperature and relative humidity, respectively. The selected reading rate for this investigation was 5 minutes, as this allowed a detailed picture of temperature variation in the accommodation rooms. One data logger was placed in each of the investigated rooms. The locations of the data loggers were selected so as to avoid direct solar radiation or proximity to other heating sources.

2.3 Thermal comfort surveys

Thermal comfort surveys were carried out in the participants' rooms. Indoor environmental measurements of air temperature, relative humidity, globe temperature and air velocity were taken during the face to face questionnaire using the portable DeltaOhm HD32.3 instrument. The questionnaire included questions about general perception of environmental conditions (including temperature and air movement), frequency of controls use and details about location of previous residence, including details of space heating and cooling facilities and ventilation strategy. For the assessment of thermal comfort at the time of the questionnaire, the 7-point ASHRAE thermal sensation scale was used (ASHRAE 2013) with 5-point thermal preference scale. Also recorded were clothing levels and reported activity level for the 30 minutes prior to the questionnaire.

Two sets of survey data are used in this analysis, both from the 2015/2016 academic year and both conducted over the first three months of the occupants one year stay (October 2015 – December 2015). The first of the two questionnaires was carried out over a fifteen day period at the end of October 2015 and the second over a fifteen day period in early December 2015. This allowed investigation of participants change in comfort temperature over time which can be considered to be evidence of adaptation.

3 Results & Discussion

3.1 Factors which could affect occupants' comfort temperature

The aim of this paper is to investigate the impact that thermal history has on comfort temperature in a new climate. However, to do this requires first that other factors that are known to impact comfort temperature and indoor climate are considered. Factors to be considered here are gender, age and building characteristics. Gender is also often considered important in understanding indoor environmental preferences (Karjalainen 2007; Wang 2006) however a previous study conducted in this building, using similar methods found it to be negligible and thus is not considered here in further detail (Amin et al. 2015).

The age distribution, shown in Figure 4, highlights a cluster of participants around the age of 18-19 (first year undergraduates) and again 22-25 (Masters). Thus, while we can see some variation in age and a few outlying values this is not deemed to be influential due to both the small number of outlying values and relatively small range in ages amongst the majority of the sample. Indeed some studies considering the effects of age on comfort typically consider groups of at least 10 years in range (Indraganti & Rao 2010) and in some cases greater, e.g. over 65 years and under 65 years (Del Ferraro et al. 2015).

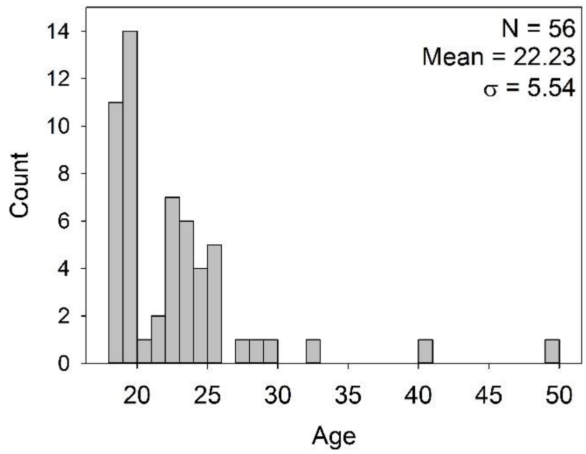

Figure 4 Histogram showing age distribution of study sample

Finally, considering building characteristics is key to understanding both user satisfaction and the indoor environment as they can have a strong influence on both of these factors. In some cases this could include building fabric but since all participants of this study are residents of the same building complex, this is negligible. In this instance, it is likely that floor level and orientation are likely to have the strongest influence on indoor temperature as the complex is split over 16 floors and the orientations of the rooms allow for vastly different levels of solar gain. Hence, rooms were clustered by orientation and floor level such that all rooms in a cluster are within three floor levels and on the same façade (within 6 rooms along) as each other. Plotting the mean monitored indoor temperature of two weeks at the end of November by cluster (Figure 5) shows the diversity in indoor temperature in rooms which cannot be explained by orientation and floor level alone; in one case (Cluster 1) a difference of over 6^{o}C. This period was chosen as it is during the heating season where occupants' are likely to have greater control to create the preferred indoor environment. This further serves to highlight both the diversity in thermal preference and that occupant behaviour is likely to be a determinant for indoor temperature.

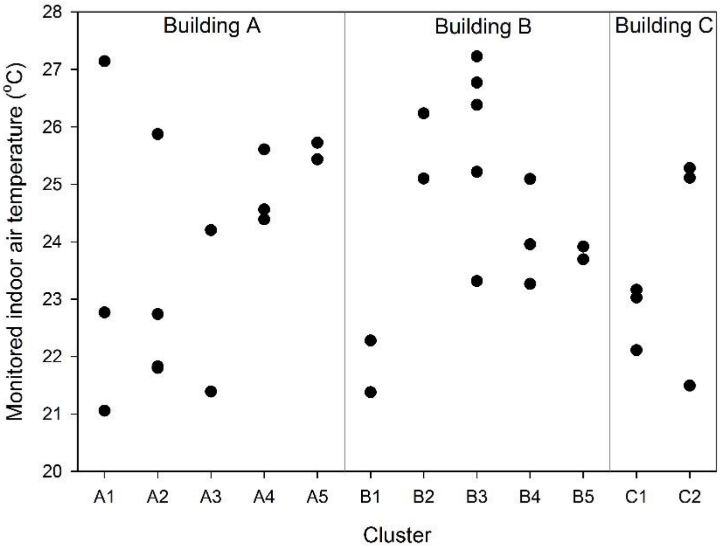

Figure 5 Mean monitored indoor air temperature for two week before second comfort survey (December 2015) clustered by orientation and floor level so that all rooms in a cluster are within 3 floor levels and on the same facade (within 6 rooms) as each other. Clusters are grouped by building (A, B, C – see Figure) where lower numbered clusters refer (approximately) to lower floor numbers.

Another interesting finding from the face-to-face questionnaire which is likely to have a strong influence in understanding the building occupants moving forward is that the range in number of hours spent in their accommodation rooms (including sleeping time) varies greatly; from 10-20 hours on weekdays and 0-22 hours on weekends. In terms of understanding the occupants from their monitored data this is likely to be of great importance in one of two ways. Either, those who spend longer in their rooms are likely to be controlling their environment to suit their preferences for much longer than their counterparts who spend fewer hours in the rooms. Alternatively, those who spend a greater number of hours in their room may adapt to their indoor environment and thus feel less of a need to take actions to modify it. In either case, monitored data from some rooms is likely to provide a more accurate picture of the occupant's preference than others.

3.2 General thermal sensation and preference

Thermal comfort surveys began shortly after the start of the 2015 Academic year in October with the first questionnaire and data logger installation taking place between 19th October and 3rd November 2015 and the second questionnaire from 30th November and 14th December 2015. The sample consisted of 56 participants, 23 males and 33 females which later reduced to 53. Figure 6 shows the distribution of thermal sensation votes and thermal preference votes across the two surveys. The thermal sensation vote (TSV) provides the participants current perception of temperature (on a 7-point scale) and the thermal preference vote (TPV) indicates their inclination to change their environment if they were able to. Figure highlights a slight shift between the two surveys moving into the heating season where there is a noticeable decrease in people reporting 'neutral' or 0. This change comes despite the fact that the range in indoor temperatures were similar during both surveys, 20.8^{o}C and 27.3^{o}C in October and 19.4^{o}C and 27.4^{o}C implying that some adaptation has taken place such that expectation of the environment has changed. Furthermore, there is evidence for a change in desire to modify their environments for the cooler. For example, in the case of TSV=+1, the number of people casting this vote is the same in both surveys but there appear to be less inclination to prefer cooler in the second survey. This is also reflected in TSV=+2 where there is no longer a participant preferring 'much cooler'.

The fact that the range of mean globe temperature recorded during the face-to-face questionnaire was between 20.8^{o}C and 27.3^{o}C in October and 19.4^{o}C and 27.4^{o}C in December serves to highlight the diversity in comfort temperatures experienced by residents as in both cases the majority found the environment satisfactory (-1 ≤TSV≤1).

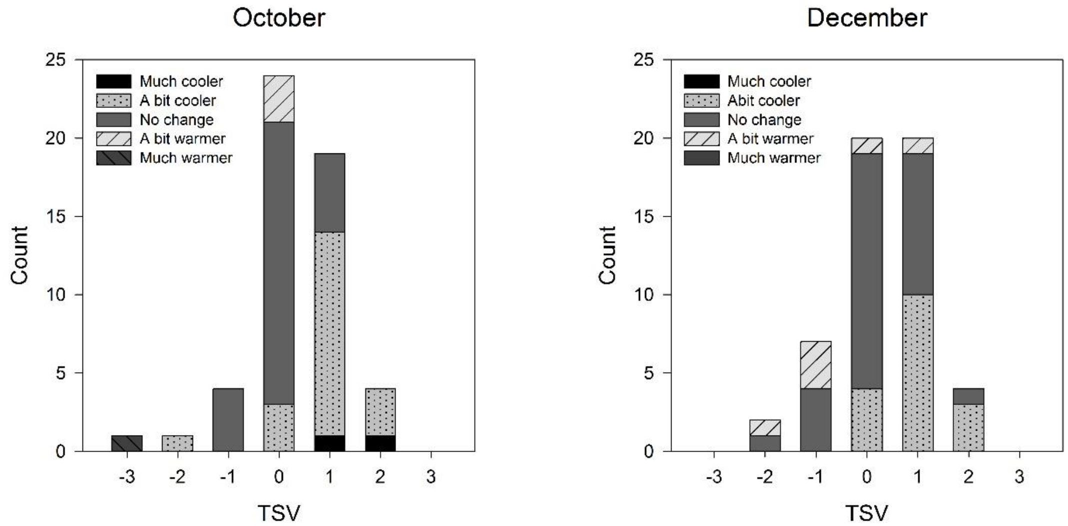

Figure 6 Histogram showing the distribution of Thermal Sensation Votes (TSV) in the October and December thermal comfort surveys along with proportion of thermal preference votes

3.3 Comfort temperatures

Comfort temperatures, T_{com}, were calculated using the Griffiths method which uses the globe (operative) temperature measured during the face-to-face questionnaire along with the thermal sensation vote. The Griffiths constant is taken to be 0.5 (Nicol & Humphreys 2010):

$$T_{com} = T_{op} + \frac{TSV}{0.5} \quad (1)$$

where T_{op} is the operative temperature at the time of the survey and TSV the thermal sensation vote.

The participants were then grouped by climate of previous residence as described in the Methodology (Section 2.1). Of the 56 participants, 23 had been living in the UK for two years prior to moving into Mayflower (Category A – UK), 19 had been in countries other than the UK that have climates as cold as or colder than the UK (Category A – NON UK) and 14 had been living in warm/hot climates (Category B).

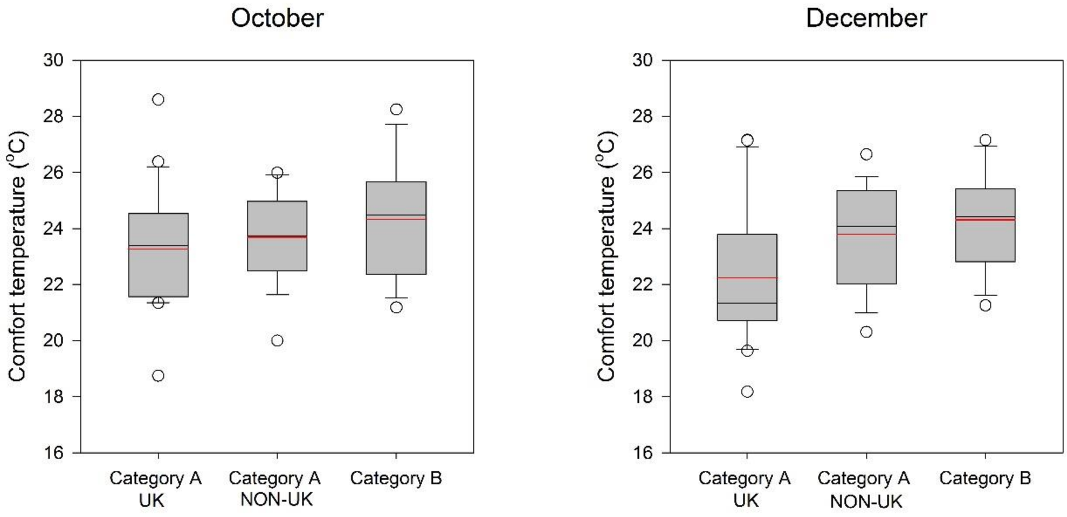

Figure 7 Box plots showing the mean (red line) median (black line), 10th, 25th, 75th, 90th percentiles and outliers (circles) of comfort temperature calculated in October where n=56 (left) and December where n=53 (right). Values are grouped by climate of residence two years prior to moving to the case study building.

Figure 7 shows box plots summarising comfort temperatures grouped by climate. The mean outdoor temperature during the October survey (n=56) was 10.6°C (σ=1.7) and during the December survey (n=53) was 10.2°C (σ=2.2). These mean outdoor temperatures are unusual for the UK, with December being 4.1°C higher than the long term average (Met Office 2016b). The means and standard deviations of the comfort temperatures for the three groups are shown in Table 1. As can be seen, the mean comfort temperature of Category B group (warm/hot 'home' climates') is approximately 1°C higher than that of the other two groups. No statistically significant difference was found between groups in the October survey (p=0.321). There was a statistically significant difference found between groups in the December survey (p=0.016), between Category A-UK and Category A NON-UK ($p<0.05$) and also between Category A-UK and Category B ($p<0.05$). It is possible that there is no statistical difference in mean comfort temperatures in the first survey as all the residents, regardless of their climate history, are adapting to very different living conditions in the halls of residence complex than they are likely to be used to.

Table 1 Summary table showing means and standard deviations of comfort temperature for October, comfort temperature for December and monitored air temperature for December (two weeks before comfort temperature calculation) for the three climate groups

	October T_{com} (°C)		December T_{com} (°C)	
	mean	σ	mean	σ
Category A- UK	23.3	2.2	22.2 [a, b]	2.4
Category A – NON UK	23.7	1.6	23.8 [a]	1.8
Category B	24.3	2.1	24.3 [b]	1.7

a – statistically significant difference Category A-UK and Category A-NON UK, $p<0.05$
b – statistically significant difference Category A-UK and Category B, $p<0.05$

Between the first and second survey there is a decrease in mean comfort temperature in Category A- UK of over 1^{o}C. The other two groups, Category A- NON UK and Category B demonstrate little to no change in mean comfort temperature from one survey to the other. This is illustrated in Figure 11 which shows the comfort temperatures of each participant in the three groups in October and December. While all groups contain individuals whose comfort temperature change (increase or decrease) dramatically (up to 4.5^{o}C) between surveys, it is clear to see that the only groups that displays a change in mean is Category A – UK. This is an interesting finding given that the ambient temperature changed very little over this period, reinforcing the fact that comfort temperature is not only determined by outdoor temperature. Taking this further, the fact that only the residents who have been living in the UK before the start of the study showed a decrease in comfort temperature could be taken as evidence of psychological adaptation. That is, since these residents are accustomed to the seasonality of the UK, they have come to expect colder temperatures and therefore subconsciously prefer them. It is possible that this is driven by other environmental cues such as shorter daylight hours. In Southampton, sunrise typically occurs at 06:28 GMT and sunset at 17:17 GMT in mid-October compared to 08:02 GMT (sunrise) and 16:00 GMT (sunset) in mid-December (HMNAO 2011).

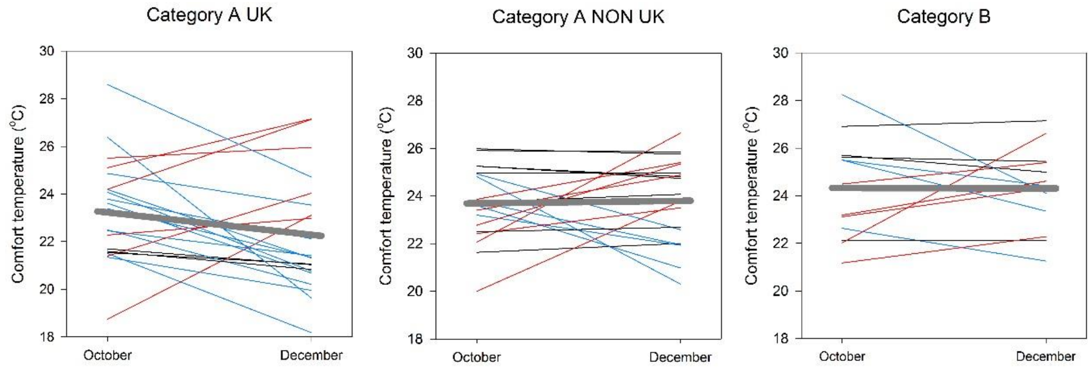

Figure 11 Change in comfort temperature from October to December and monitored indoor temperature in December grouped by climate of residence for 2 years prior to moving to Mayflower halls of residence. Red lines indicates increase in comfort temperature, blue lines indicates decrease in comfort temperature and black lines indicates negligible change in comfort temperature (<0.75°C). Bold grey line indicates change in mean comfort temperature.

Figure 9 shows the daily mean monitored indoor air temperature for the 53 participants who completed both thermal comfort surveys for the period between the two surveys (04/11/15 – 29/11/15) grouped by Category. Also shown is the ambient temperature. Most noticeable is the sharp drop in outdoor temperature on the 22nd November which corresponds to sharp drops in daily mean indoor temperatures in a few rooms which is likely to be a result of windows left open and radiator set on either low or off during this period. Considering that many of the rooms maintain very stable temperatures during this period, it is significant that the rooms with greatest drops in temperature are in Category A-UK, as leaving windows open is behaviour consistent with trying to achieve cooler temperatures. This agrees with the findings of the thermal comfort surveys and implies a move towards cooler temperature in the Category A-UK group and not in the other groups.

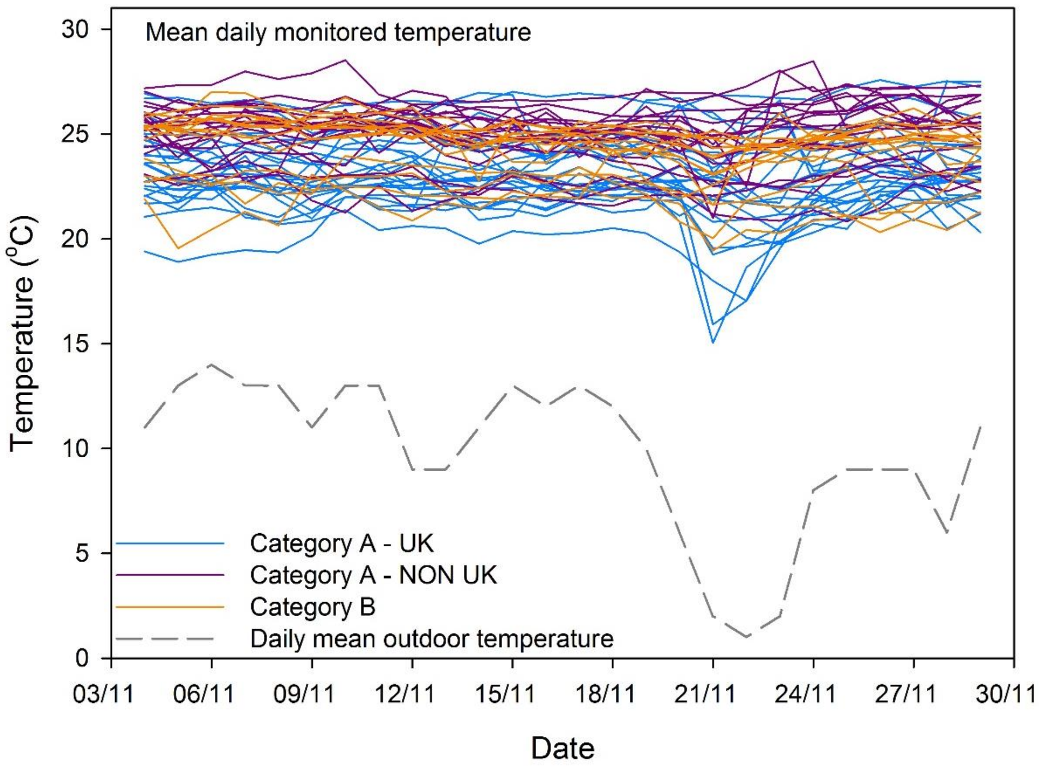

Figure 9 Mean daily monitored air temperature from 53 accommodation rooms in Mayflower Halls for the period between the first and second thermal comfort survey (04/11/15-29/11/15) coloured by climate of residence prior to moving to the case study building

The final relationship considered in this study was the fundamental adaptive relationship of indoor temperature and comfort temperature. Figure 10 shows a scatter plot of mean comfort temperature of the two surveys against mean indoor monitored temperature for the period between the two surveys. The correlation coefficient, r, for all data points was found to be 0.51 ($p<0.05$) however more interesting is the difference in correlation between the 3 categories. The correlation coefficients were found to be 0.69 ($p<0.05$), 0.14 ($p>0.05$) and 0.28 ($p>0.05$) for Category A UK, Category A NON UK and Category B, respectively. There is no significant relationship between comfort temperature and indoor temperature in either Category A NON UK or Category B but there is in Category A. This shows that indoor temperature is a good indicator of comfort temperature in residents who are already adapted to the UK conditions but not for residents who are not. Some of the scatter seen here may be due to the fact that both surveys considered here are early in the occupancy period and residents may still be familiarising themselves with their new environment. Furthermore, the data used to calculate the average indoor temperature included unoccupied periods; if the exact occupancy schedules were known, a stronger relationship may have been observed. However, it is evident that occupants from the UK are better able to control their environment to suit their comfort.

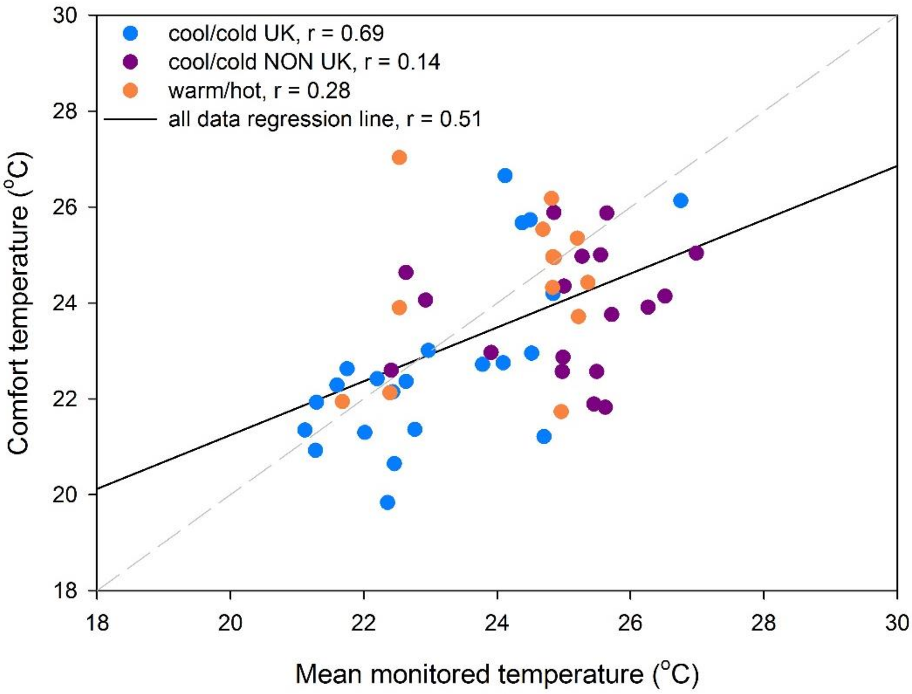

Figure 10 Relationship between comfort temperature and mean indoor temperature. The comfort temperature is the average of the two surveys and the mean monitored temperature is for the period between the two surveys. The solid line shows the regression line for all data values and the correlation coefficients for the individual groups are shown in the legend.

4 Conclusions

This study has investigated thermal preferences of occupants of Mayflower halls of residence complex in Southampton, UK using a mixed methods approach. It has been shown that variation in monitored air temperature cannot be attributed only to orientation and floor level in this case and furthermore that residents have reported feeling neutral (on a 7 point ASHRAE scale) within a wide range of measured globe temperatures. Differences in comfort temperature of over 10°C were found across two thermal comfort surveys conducted in October and December (within the first three months of the occupants stay). The first survey (October) found no statistically significant difference in comfort temperature of occupants when grouped by climate of residence for two years prior to moving to Mayflower, however a significant difference had emerged by the time of the second survey (December). One-way ANOVA revealed a statistically significant difference in comfort temperature between residents from Category A-UK and both Category A-NON UK and Category B, where the mean comfort temperature of the Category A-UK group had decreased by 1°C and the others had remained the same. This arose despite very little change in ambient temperature due to an unseasonably warm winter during the study period. This could be evidence of psychological adaptation, whereby residents accustomed to the seasonality of the UK expect cooler conditions and therefore come to prefer them. Cues here could include changes in daylight hours and perhaps wider media relating to this time of year. Furthermore, consideration of indoor temperature and comfort temperature revealed that this relationship is much stronger for residents from the

UK, which indicates that their adaptation to the local conditions means that they are better able to control their environment to suit their comfort. While the limited number of surveys conducted so far mean that these findings are far from conclusive, it provides insight into thermal history and expectation in the context of a new climate. Subsequent surveys to be conducted over the coming months will strengthen the evidence base.

Acknowledgements

The authors would like to thank the participants in this study for their ongoing cooperation. This work is part of the activities of the Energy and Climate Change Division at the University of Southampton and is also supported by funding from the Engineering and Physical Sciences Research Council (EPSRC) through a Doctoral Training Partnership and the Transforming Engineering of Cities Programme grant EP/J017298/1.

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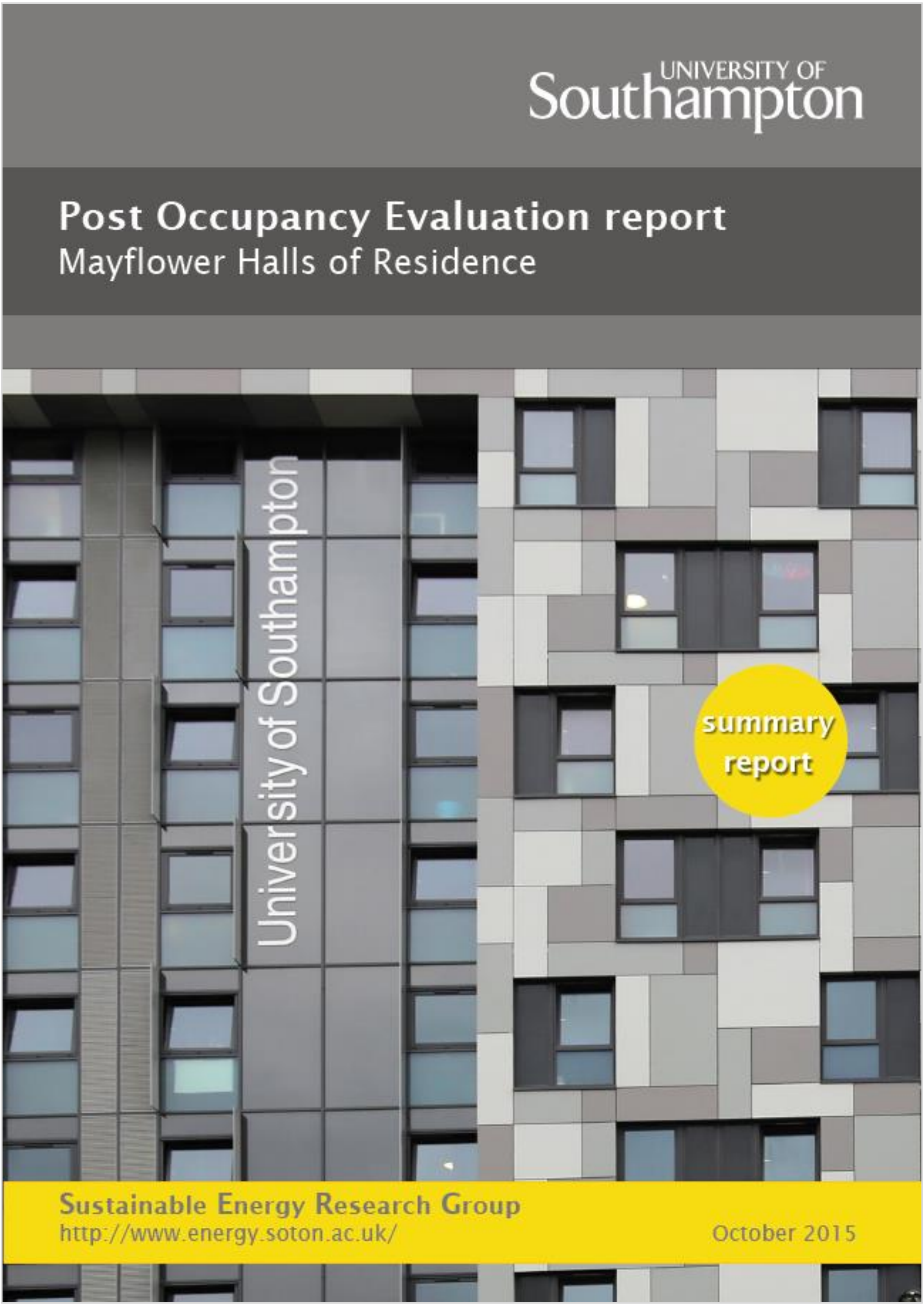
IV – Post Occupancy Evaluation Report



Authors:
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The Sustainable Energy Research Group (SERG) aims to promote and undertake fundamental and applied research related to the efficient use of energy in the built environment. This is alongside pre-industrial development in the areas of renewable energy technologies. SERG undertakes research in core areas of energy, specifically in Cities and Infrastructure, Energy and Behaviour, Energy and Buildings and Renewable Energy (Solar Photovoltaics and Marine Energy).

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Sustainable Energy Research Group (SERG) UNIVERSITY OF Southampton

The buildings

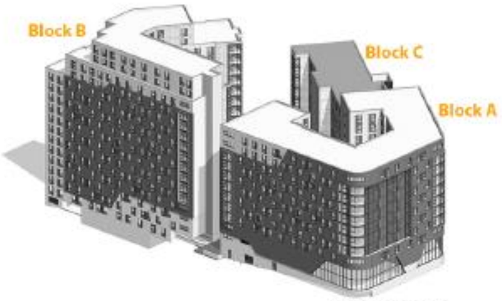
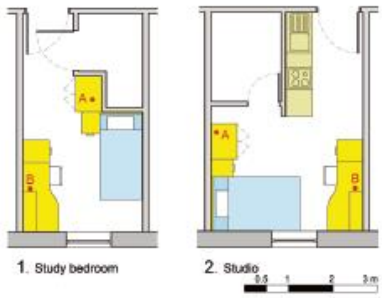


Image source: [1]

The Mayflower Halls complex is a £70 million building development in Southampton, UK. The site covers an area of approximately 0.6 hectares. The building development consists of three buildings (Blocks A, B and C) that offer a total of 1,104 units for student accommodation, main reception areas, common spaces and facilities, such as laundry and a gym.

There are three types of accommodation provided throughout the building complex: en suite study bedrooms, self-contained studios (plans on the right) and one-bedroom suites.

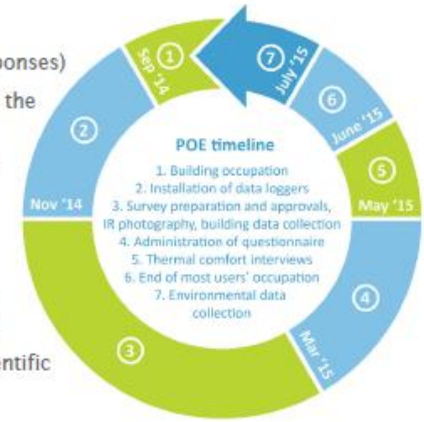
The buildings were awarded a BREAAM Excellent rating and the University of Southampton committed to providing the best possible student living experience, while at the same time achieving high building energy efficiency and optimal internal conditions.



POE methodology

The Mayflower Halls POE method included:

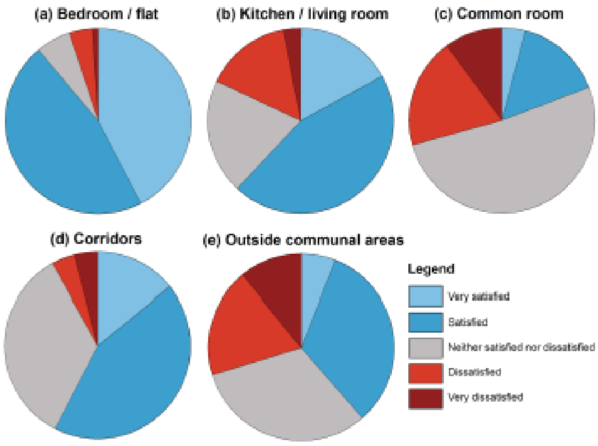
1. Web based structured questionnaires (223 responses)
2. Water and electricity usage data collected from the buildings' monitoring systems
3. Five-min air temperature and relative humidity measurements from the accommodation units
4. Interviews and thermal comfort surveys with occupants and the halls' managers
5. Information from the developer, the University of Southampton and the Halls' management team
6. Walkthroughs observations with the use of scientific equipment (e.g. Infrared camera)



1

Occupant survey

An online questionnaire was sent by email to 955 (out of a total 1,029) residents of Mayflower Halls of Residence in March 2015 using the University of Southampton's iSurvey software. From the initial sample, 298 participants (31%) responded to the survey. The complete, valid questionnaires were 223 (n=223), representing a response rate of 23%.



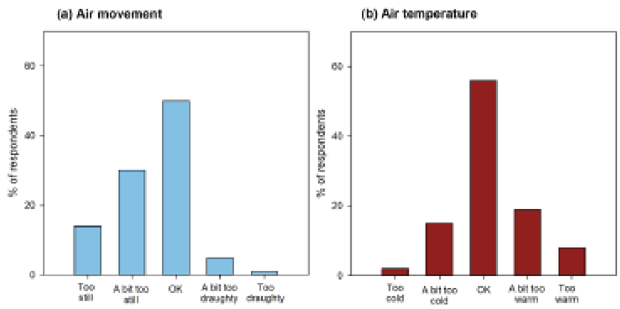
Overall, there is a high level of satisfaction with the building spaces and facilities (image on the left).

The building scored very well with regards to its location and the proximity to the city centre and the railway station.

Artificial lighting and daylighting levels were found to be adequate and most of the occupants were satisfied with the lighting conditions.

There were some concerns regarding noise, but this was mainly due to construction works taking place around and inside the buildings at the first months of occupation. This affected a number of occupants but it is unlikely to reoccur as the works have now been completed. It should be noted that the Halls are built in a premium central location and some noise disturbance is to be expected.

The majority of the occupants are satisfied with the air temperature in the rooms. However, there are 30% who find the temperature "a bit" or "too hot". These responses are supplemented by comments on limited air movement. Overall, the percentage of those that voted "too still" is quite low (14%) to suggest that there is a general, large problem with ventilation in the buildings.



Note: The negative responses in winter can be attributed to improper control of the thermostatic radiator valve (TRV) and lack of an understanding on how the radiators work.

Success factors/good practice

High occupant satisfaction with the building spaces and facilities, location, room layout, lighting, indoor environment

Issues for improvement

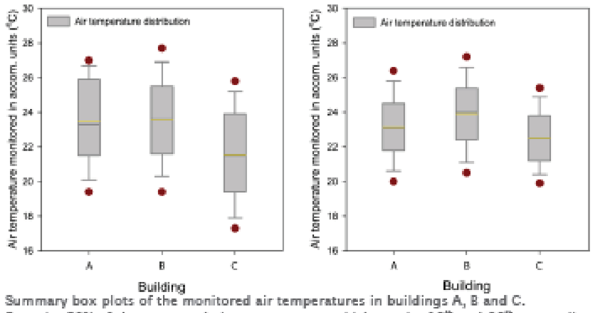
Some concerns on ventilation rates and warm temperatures
Improper control of TRVs

2

Environmental monitoring

Temperature and relative humidity sensors with miniature data loggers were placed in 73 accommodation units. A random sample of rooms at all three blocks had been selected aiming to represent all locations within the building complex, floor levels and orientations.

Overall, temperature in the rooms remained high both in winter and summer.



Summary box plots of the monitored air temperatures in buildings A, B and C.
Box: the 50% of the measured air temperatures; whiskers: the 10th and 90th percentile; red dots: the 5th and 95th percentile; grey line: median, yellow line: mean.

Occupants of buildings such as the Mayflower Halls have a very mixed climatic background and diverse perception of thermal comfort conditions. The high degree of satisfaction with air temperature (~60%) reported in the survey can mean that occupants prefer the temperature at these high levels.

Winter

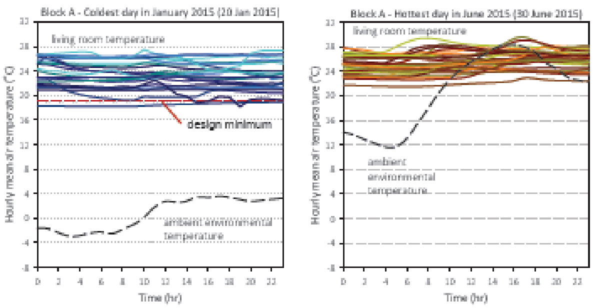
During the heating season most of the rooms were heated to internal temperatures well above the 19°C that was the design minimum requirement [2].

Summer

A large number of accommodation units in Blocks A and B had temperatures above 24°C for at least 50% of the monitoring time. Rooms towards the top floor had a higher mean temperature than the rooms in low floor levels, which was more critical for south orientated rooms compared to north orientated. In Block B, the rooms at high floor levels had a temperature above 22°C for 95% of the monitored time.

On the coldest winter day, the temperature in the accommodation units remains stable and high during the 24-hour period (block A example on the right).

On the hottest of the occupied days room temperatures in block A remain overall stable and range between 21-29°C. The temperature spikes are strongly related to room orientation. Similar results were obtained in the other 2 blocks.



Note: The hottest day shown is not representative of heat wave conditions in the UK. It is expected that during a heat wave the room temperatures would increase above the temperature levels shown here.

Success factors/good practice

Winter air temperatures were above the design minimum.
95% of the monitored relative humidity values are between 30-60%

Issues for improvement

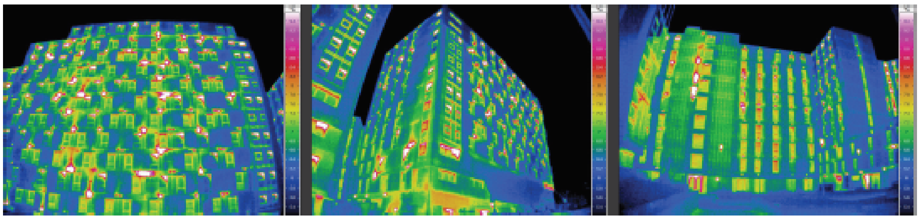
In summer, rooms at high floor levels in Blocks A and B have a high likelihood to experience high temperatures during hot weather

3

Walkthrough surveys

Infrared images of the main facades were taken early morning in the winter. The thermal images show the surface temperature of the materials. The colour scale ranges from 5.4°C (dark blue) to 9.4°C (pink). The white colour is "burnt" out of scale pixels, which means hotter than the scale shown. The thermal imaging reveals that there are not any long thermal bridges in the building envelope that would raise concerns. Windows and their frames have higher surface temperatures as expected but comparable to the cladding.

The main heat losses identified are from the extract fans' ducts (small circular shaped white spots), open windows, trickle vents and the entrance of the building blocks. The existence of such a large number of open room windows in a cold winter night shows that several occupants felt too warm in their room.



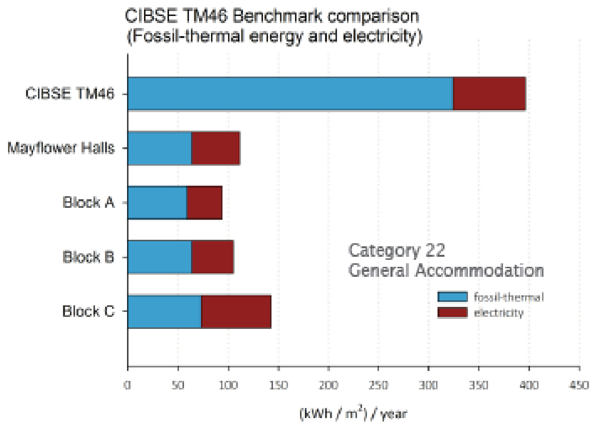
Energy and water usage audit

Metered electricity, heat and water consumption summaries were used to assess the buildings' efficiency and to compare with CIBSE benchmarks [3].

Annual total water usage
33.8 m³/accommodation unit (i.e. 93 L/accom. unit . day), about 25% less than the typical usage for 1 person of 45-50 m³ per year [4,5].

Annual electricity usage
47.4 kWh/m²/year, 35% lower than the CIBSE benchmarks.

Annual heat demand
64 kWh/m²/year, only 20% of the typical fossil-thermal energy consumption of this benchmark category.



Success factors/good practice

Air-tight building envelope, without long thermal bridges.
Very good performance regarding electricity, water usage and heat demand

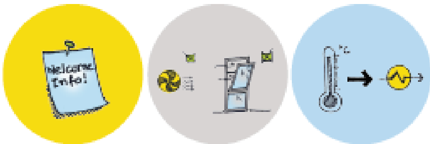
Issues for improvement

In winter a number of occupants open the windows increasing the ventilation losses

4

Recommendations for improvement

Winter



A. Occupant training

Print outs with instructions and guidelines on the use of the thermostatic radiator valve, trickle vents and extract fan. Any guiding material must clearly demonstrate the connection between room air temperature and the thermostatic radiator valve settings (e.g. explain what 4 out of 5 on the TRV means in terms of room temperature achieved). Pilot studies looking at the effectiveness of 1) guidance material, 2) simple wall mounted indoor weather stations with a LCD display and 3) prefixed radiator settings can point out a cost-effective course of action.

B. Decrease of ventilation losses

Automatic boost of the extract fan in the rooms in the morning, after lunch and dinner time in order to increase the ventilation rates. This measure aims to prevent the occupants from opening the window for prolonged periods of the day.

C. Indoor temperature control

Dynamic control of the heat exchangers output. Regulate the flow rate in relation to ambient temperature and internal building temperature.

Summer

D. Occupancy management

The halls of residence are not occupied at their full nominal capacity in July and August, when the outdoor temperature remains high for prolonged periods of time. A simple solution would be to organise and arrange so as the long-term lease students occupy the coolest parts of the building complex. Any summer school/foundation students could also be allocated to north and south orientated rooms, starting with low building floor levels first. In that way, there is a high likelihood that study bedrooms with a high risk of overheating will be unoccupied during the periods of hot weather.

E. Increase of ventilation potential

One-bedroom suites and studios at top floors could be equipped with ceiling fans. The thermostatic control of the extractor fans and the use of ceiling fans could help to alleviate any issues with air movement and increase the natural ventilation cooling potential.

F. Solar shading

Additional shading in the form of highly reflective blinds, window films, external shade features or different type of curtains (light colour), should be considered for the rooms facing southeast and northwest. Priority should be given to rooms at high levels.

5

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6

Appendix B

Questionnaires

I – Pilot study questionnaire

UNIVERSITY OF Southampton

Mayflower Halls Thermal Comfort Study

May 2015

As part of the building planning conditions and the continuous improvements of the University to its services, we are required to assess the building's operation and performance. To do this, we need your help!

This questionnaire also gives you the opportunity to express your views about the building and how we may improve it in the future. Your responses will be anonymous and all data will be handled in accordance with the Data Protection Act 1998.

This study is also part of research on energy efficiency and thermal comfort in buildings conducted by the Sustainable Energy Research Group at the University of Southampton (www.energy.soton.ac.uk).

I agree to take part in the research study and agree for my data to be used for the purpose of this study.	☐
Signed ………………………………………………………………………	

Equipment ID:	15001976 / 15001971	Log session:	
Date:		Time:	

Section 1: About You

1.1 Building:		1.2 Flat:		1.3 Room:	

1.4 Gender:	M / F	1.5 Age:	

1.6 Country of residence for last 2 years:	
1.7 City of residence for last 2 years (before Sept 2014)	

1.8 Level of study:

1st year UG	2nd year UG	3rd year UG	4th year UG	PGR taught/research	PhD	Other/ Staff
☐	☐	☐	☐	☐	☐	☐

1

Mayflower Halls Thermal Comfort Study
Section 2: Post Occupancy Evaluation

2.1 Mayflower Building

2.1.1 On a typical **weekday**, how many hours do you spend in the following spaces?	
Bedroom/Flat (including sleeping time):	hours
Kitchen/Living Room:	hours
Common Room:	hours

2.1.2 On a typical **weekend day**, how many hours do you spend in the following spaces?	
Bedroom/Flat (including sleeping time):	hours
Kitchen/Living Room:	hours
Common Room:	hours

2.1.3 How satisfied are you with the following spaces where 1 is very dissatisfied, 3 is neutral and 5 is very satisfied? Specifically, to what extent do you feel they meet your needs?

	Very dissatisfied	Dissatisfied	Neither satisfied nor dissatisfied	Satisfied	Very satisfied
Bedroom/Flat	☐	☐	☐	☐	☐
Kitchen/Living Room	☐	☐	☐	☐	☐
Common Room	☐	☐	☐	☐	☐
Corridors	☐	☐	☐	☐	☐
Outside communal area	☐	☐	☐	☐	☐

2.1.3a If dissatisfied with any of the spaces, please could you explain why:

2

Mayflower Halls Thermal Comfort Study

2.1.4 **In general**, how would you describe the temperature in the kitchen?				
Too cold	A bit too cold	Ok	A bit too warm	Too warm
☐	☐	☐	☐	☐

2.1.5 **In general**, how would you describe the air movement in the kitchen?				
Too still	A bit too still	Ok	A bit too draughty	Too draughty
☐	☐	☐	☐	☐

2.1.6 How easy is it to access the facilities available to you from your floor? E.g. laundry room, cycle store etc.				
Very difficult	Difficult	Neither easy nor difficult	Easy	Very easy
☐	☐	☐	☐	☐

2.1.7 How satisfied are you with the location of the building with respect to:					
	Very dissatisfied	Dissatisfied	Neither satisfied nor dissatisfied	Satisfied	Very satisfied
Highfield campus	☐	☐	☐	☐	☐
Avenue campus	☐	☐	☐	☐	☐
National Oceanography Centre (NOC)	☐	☐	☐	☐	☐
City Centre	☐	☐	☐	☐	☐
Southampton Central train station	☐	☐	☐	☐	☐

3

2.1.8 Are you aware of the "Meet the Manager" sessions?	
Yes	☐
No	☐
2.1.8a **IF YES:** Have you ever attended a "Meet the Manager" session?	
Yes	☐
No – I have had no issues to report	☐
No – I have not had the time	☐

2.1.9 Are you aware of the "PlanOn" reporting system?	
Yes	☐
No	☐
2.1.9a **IF YES:** Have you ever used the "PlanOn" reporting system?	
Yes	☐
No – I have had no issues to report	☐
No – I found the process too complicated	☐

2.1.10 Have you spent an extended period of time away from the halls (over 2 weeks) e.g. at Christmas or Easter		
	Tick if yes	Number of weeks
Christmas	☐	
Easter	☐	
Other:	☐	
Other:	☐	

Mayflower Halls Thermal Comfort Study

Section 2.2 Bedroom/Flat

2.2.1 **In general**, how would you describe the air movement in your room?				
Too still	A bit too still	Ok	A bit too draughty	Too draughty
☐	☐	☐	☐	☐

2.2.2 **In general**, how would you describe the temperature in your room during the winter?				
Too cold	A bit too cold	Ok	A bit too warm	Too warm
☐	☐	☐	☐	☐

2.2.3 What would you say your ideal indoor temperature would be in **winter**? (°C)							
14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30
☐	☐	☐	☐	☐	☐	☐	☐
30-32	32-34	As it is now	Don't know	Other (specify):			
☐	☐	☐	☐				

2.2.4 What would you say your ideal indoor temperature would be in **summer**? (°C)							
14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30
☐	☐	☐	☐	☐	☐	☐	☐
30-32	32-34	As it is now	Don't know	Other (specify):			
☐	☐	☐	☐				

2.2.5 **In general**, how would you describe the **artificial** lighting in your room?				
Too dark	A bit too dark	Ok	A bit too bright	Too bright
☐	☐	☐	☐	☐

5

2.2.6 **In general**, how would you describe the **natural** lighting level?				
Too dark	A bit too dark	Ok	A bit too bright	Too bright
☐	☐	☐	☐	☐

2.2.7 **In general**, how would you describe the background noise level?		
Too noisy	A bit too noisy	Ok
☐	☐	☐

2.2.8 **In general**, how often do you adjust the following in your room:					
	Never *< once per month*	Rarely *Once per week*	Sometimes *1-2 times per week*	Often *Daily*	Frequently *> once per day*
Artificial Lighting	☐	☐	☐	☐	☐
Blinds/Curtains	☐	☐	☐	☐	☐
Windows	☐	☐	☐	☐	☐
Heater	☐	☐	☐	☐	☐

2.2.9 **In general**, how often do you use the following in your room:					
	Never *< once per month*	Rarely *Once per week*	Sometimes *1-2 times per week*	Often *Daily*	Frequently *> once per day*
Additional bedding	☐	☐	☐	☐	☐
Additional lighting	☐	☐	☐	☐	☐
Other (specify):	☐	☐	☐	☐	☐

Mayflower Halls Thermal Comfort Study

2.2.10 Do you have any further comments about the environmental conditions in your bedroom? (*Optional*)

7

Mayflower Halls Thermal Comfort Study

Section 3: Thermal Comfort (Current comfort conditions)

3.1a In terms of temperature, how do you feel at the moment?						
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
☐	☐	☐	☐	☐	☐	☐

3.1b How would you prefer to feel?				
Much cooler	A bit cooler	No change	A bit warmer	Much warmer
☐	☐	☐	☐	☐

3.2a How do you find the air movement?						
Very low	Low	Slightly low	Neither high nor low	Slightly high	High	Very high
☐	☐	☐	☐	☐	☐	☐

3.2b What would you prefer to have?				
Much less air movement	A bit less air movement	No change	A bit more air movement	Much more air movement
☐	☐	☐	☐	☐

3.3a How do you find the humidity?						
Very dry	Dry	Slightly dry	Neither humid nor dry	Slightly humid	Humid	Very humid
☐	☐	☐	☐	☐	☐	☐

3.3b What would you prefer to have?				
Much drier	A bit drier	No change	A bit more humid	Much more humid
☐	☐	☐	☐	☐

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Mayflower Halls Thermal Comfort Study

3.4 How would you rate your overall comfort?					
Very uncomfortable	Moderately uncomfortable	Slightly uncomfortable	Slightly comfortable	Moderately comfortable	Very comfortable
☐	☐	☐	☐	☐	☐

3.5 Clothing Level (tick as appropriate):			
Short sleeve shirt/blouse	☐	Long socks	☐
Long sleeve shirt/blouse	☐	Short socks	☐
Vest	☐	Tights	☐
Trousers/ Long skirt	☐	Tie	☐
Shorts/ short skirt	☐	Boots	☐
Dress	☐	Shoes	☐
Pullover	☐	Sandals	☐
Jacket	☐	Other (specify)	☐

3.6 Activity level in the last hour (tick as appropriate):			
Sitting (passive work)	☐	Standing working	☐
Sitting (active work)	☐	Walking indoors	☐
Standing relaxed	☐	Walking outdoors	☐
Other (specify):			☐

3.7 Controls (tick as appropriate):			Comments/Settings
Internal door	Open ☐	Closed ☐	
Window	Open ☐	Closed ☐	

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Mayflower Halls Thermal Comfort Study

Blinds/Curtains	Open ☐	Closed ☐	
Heating	On ☐	Off ☐	
Lighting	On ☐	Off ☐	

END

NOTES
Location of measurement kit: Other:

10

II – Face-to-face questionnaire

Mayflower Halls Thermal Comfort Study

University of Southampton

October 2015

This study is part of a PhD research project on energy efficiency and thermal comfort in buildings conducted by a student of the Sustainable Energy Research Group at the University of Southampton (www.energy.soton.ac.uk).

Participation is voluntary and you are free to opt out at any time. Your responses will be anonymous and all data will be handled in accordance with the Data Protection Act 1998.

I agree to take part in the research study and agree for my data to be used for the purpose of this study.	☐
Signed	

Logger ID:		Location:	
Date:		Time:	

Section 1: About You

1.1 Building:		1.2 Room		1.3 Flat	

1.4 Gender:	M / F	1.5 Age:	

1.6 Level of study:						
1st year UG ☐	2nd year UG ☐	3rd year UG ☐	4th year UG ☐	PGR taught/research ☐	PhD ☐	Other / Staff ☐

1.7 Country of residence for last 2 years:	
1.8 City of residence for last 2 years (before Sept 2015)	

1.9 Did you have a HEATING system in your previous residence:	Yes / No
1.10 If yes, do you know what type?	
1.11 How frequently did YOU personally adjust settings on the heating system?	
1.12 Did you have an AIR CONDITIONING system in your previous residence?	Yes / No
1.13 Is air conditioning use typical in homes during your summer period?	Yes / No

1

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Mayflower Halls Thermal Comfort Study

1.14 What would you say your ideal indoor temperature would be in **winter?** (◦C)							
14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30
□	□	□	□	□	□	□	□
30-32	32-34	As it is now	Don't know	Other (specify):			
□	□	□	□				

1.15 What would you say your ideal indoor temperature would be in **summer?** (◦C)							
14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30
□	□	□	□	□	□	□	□
30-32	32-34	As it is now	Don't know	Other (specify):			
□	□	□	□				

2. Mayflower Building & Bedroom

2.1 **In the past 2 weeks,** how would you describe the temperature in your **room**?				
Too cold	A bit too cold	Ok	A bit too warm	Too warm
□	□	□	□	□

2.2 **In the past 2 weeks,** how would you describe air movement in your **room**?				
Too cold	A bit too cold	Ok	A bit too warm	Too warm
□	□	□	□	□

2

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Mayflower Halls Thermal Comfort Study

2.3 **In the last two weeks,** how often have you done the following in **your room**:						
	Never *< once per month*	Rarely *Once per week*	Sometimes *1-2 times per week*	Often *Daily*	Frequently *> once per day*	**If "never"**, what is the default setting?
Open Blinds/Curtains	☐	☐	☐	☐	☐	
Open Windows	☐	☐	☐	☐	☐	
Turn on Heater	☐	☐	☐	☐	☐	
Other (specify):	☐	☐	☐	☐	☐	

Section 3: Thermal Comfort (Current comfort conditions)

3.1a In terms of temperature, how do you feel at the moment?						
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
☐	☐	☐	☐	☐	☐	☐

3.1b How would you prefer to feel?				
Much cooler	A bit cooler	No change	A bit warmer	Much warmer
☐	☐	☐	☐	☐

3.2a How do you find the air movement?						
Very low	Low	Slightly low	Neither high nor low	Slightly high	High	Very high
☐	☐	☐	☐	☐	☐	☐

3.2b What would you prefer to have?				
Much less air movement	A bit less air movement	No change	A bit more air movement	Much more air movement
☐	☐	☐	☐	☐

3.3a How do you find the humidity?						
Very dry	Dry	Slightly dry	Neither humid nor dry	Slightly humid	Humid	Very humid
☐	☐	☐	☐	☐	☐	☐

3.3b What would you prefer to have?				
Much drier	A bit drier	No change	A bit more humid	Much more humid
☐	☐	☐	☐	☐

3

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Mayflower Halls Thermal Comfort Study

3.4 How would you rate your overall comfort?					
Very uncomfortable	Moderately uncomfortable	Slightly uncomfortable	Slightly comfortable	Moderately comfortable	Very comfortable
□	□	□	□	□	□

3.5 What do you think the air temperature is at the moment?	°C	Don't know □

3.6 Clothing Level (tick as appropriate):			
Short sleeve shirt/blouse	□	Long socks	□
Long sleeve shirt/blouse	□	Short socks	□
Vest	□	Tights	□
Trousers/ Long skirt	□	Tie	□
Shorts/ short skirt	□	Boots	□
Dress	□	Shoes	□
Pullover	□	Sandals	□
Jacket	□	Other (specify)	□

3.7 Activity level in the last hour (tick as appropriate):			
Sitting (passive work)	□	Standing working	□
Sitting (active work)	□	Walking indoors	□
Standing relaxed	□	Walking outdoors	□
Other (specify):			□

3.8 Controls (tick as appropriate):			Comments/Settings
Internal door	Open □	Closed □	
Window	Open □	Closed □	
Blinds/Curtains	Open □	Closed □	
Heating	On □	Off □	
Lighting	On □	Off □	

Equipment ID:	15001976 / 15001971	Log session:	
Date:		Time:	

4

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Mayflower Halls Thermal Comfort Study

END

NOTES
Location of measurement kit: Other:

5

III - App study background questionnaire

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Mayflower Halls Thermal Comfort Study

October 2016

Consent form ID	

Logger ID:		Location:	

Section 1: About You

1.1 Building:		1.2 Room		1.3 Flat	

Gender	M / F	Age		Height	
Weight (kg)					

40-49	50-59	60-69	70-79	80-89	90-99	100-109	110-119	Other	Unknown
□	□	□	□	□	□	□	□	□	□

1.6 Level of study:

1st year UG	2nd year UG	3rd year UG	4th year UG	PGR taught/research	PhD	Other / Staff
□	□	□	□	□	□	□

1.7 Which country have you mostly been living in for the last 2 years:	
1.8 Which city have you mostly been living in for the last 2 years (before Oct 2016)	
1.9 Have you ever lived in anywhere other than there? *(above)*	Yes / No
1.10 If yes, please can you provide details *(where, how long etc)*	

1.11 Did you have a HEATING system in your previous residence:					Yes / No
1.12 If yes, do you know what type? *(See picture sheet)*					A / B / C / D /…/ NA
1.13 How frequently did YOU personally adjust settings on the heating system?					
Never *< once per month*	Rarely *Once per week*	Sometimes *1-2 times per week*	Often *Daily*	Frequently *> once per day*	NA
□	□	□	□	□	□
1.14 Did you have an AIR CONDITIONING system in your previous residence?					Yes / No
1.15 Is air conditioning use typical in homes during your summer period?					Yes / No / NA

1

Mayflower Halls Thermal Comfort Study

1.16 How was your previous residence ventilated? Was it:					
Naturally ventilated *The only way to draw in fresh air was to open windows*	☐	Fully mechanically ventilated *All fresh air from outside entered via vents. There are NO openable windows*	☐	Mixed mode *There are both openable windows and a mechanical system*	☐

1.17 What would you say your ideal indoor temperature would be in **winter?** (◦C)							
14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30
☐	☐	☐	☐	☐	☐	☐	☐
30-32	32-34	As it is now	Don't know	Other (specify):			
☐	☐	☐	☐				

1.18 What would you say your ideal indoor temperature would be in **summer?** (◦C)							
14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30
☐	☐	☐	☐	☐	☐	☐	☐
30-32	32-34	As it is now	Don't know	Other (specify):			
☐	☐	☐	☐				

2. Mayflower Building & Bedroom

2.1 **In the past 2 weeks**, how would you describe the temperature in your **room**?				
Too cold	A bit too cold	Ok	A bit too warm	Too warm
☐	☐	☐	☐	☐

2.2 **In the past 2 weeks**, how would you describe air movement in your **room**?				
Too cold	A bit too cold	Ok	A bit too warm	Too warm
☐	☐	☐	☐	☐

2

Mayflower Halls Thermal Comfort Study

2.3 **In the last two weeks,** how often have you done the following in **your room**:						
	Never *< once per month*	Rarely *Once per week*	Sometimes *1-2 times per week*	Often *Daily*	Frequently *> once per day*	**If "never"**, what is the default setting?
Open Blinds/Curtains	□	□	□	□	□	
Open Windows	□	□	□	□	□	
Turn on Heater	□	□	□	□	□	
Other (specify):	□	□	□	□	□	

Section 3: Thermal Comfort (Current comfort conditions)

3.1a In terms of temperature, how do you feel at the moment?						
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
□	□	□	□	□	□	□

3.1b How would you prefer to feel?				
Much cooler	A bit cooler	No change	A bit warmer	Much warmer
□	□	□	□	□

3.2a How do you find the air movement?						
Very low	Low	Slightly low	Neither high nor low	Slightly high	High	Very high
□	□	□	□	□	□	□

3.2b What would you prefer to have?				
Much less air movement	A bit less air movement	No change	A bit more air movement	Much more air movement
□	□	□	□	□

3.3a How do you find the humidity?						
Very dry	Dry	Slightly dry	Neither humid nor dry	Slightly humid	Humid	Very humid
□	□	□	□	□	□	□

3.3b What would you prefer to have?				
Much drier	A bit drier	No change	A bit more humid	Much more humid
□	□	□	□	□

3

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Mayflower Halls Thermal Comfort Study

3.4 How would you rate your overall comfort?					
Very uncomfortable	Moderately uncomfortable	Slightly uncomfortable	Slightly comfortable	Moderately comfortable	Very comfortable
□	□	□	□	□	□

3.5 What do you think the air temperature is at the moment?	°C	Don't know □

3.6 Clothing Level (tick as appropriate):			
Short sleeve shirt/blouse	□	Long socks	□
Long sleeve shirt/blouse	□	Short socks	□
Vest	□	Tights	□
Trousers/ Long skirt	□	Tie	□
Shorts/ short skirt	□	Boots	□
Dress	□	Shoes	□
Pullover	□	Sandals	□
Jacket	□	Other (specify)	□

3.7 Activity level in the last hour (tick as appropriate):			
Sitting (passive work)	□	Standing working	□
Sitting (active work)	□	Walking indoors	□
Standing relaxed	□	Walking outdoors	□
Other (specify):			□

3.8 Controls (tick as appropriate):			Comments/Settings
Internal door	Open □	Closed □	
Window	Open □	Closed □	
Blinds/Curtains	Open □	Closed □	
Heating	On □	Off □	
Lighting	On □	Off □	

Equipment ID:	15001976 / 15001971	Log session:	
Date:		Time:	

4

UNIVERSITY OF Southampton

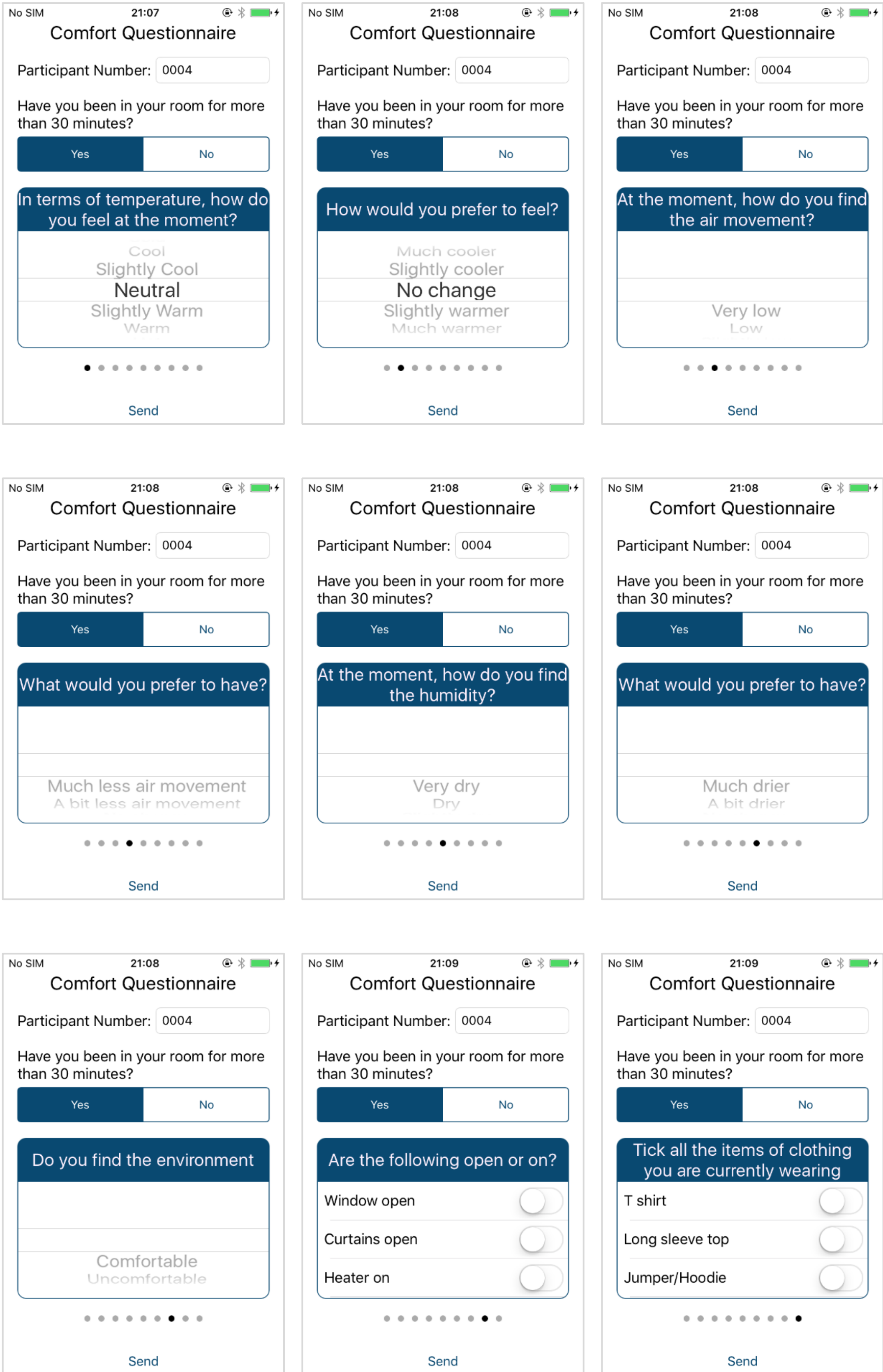
Mayflower Halls Thermal Comfort Study

END

NOTES
Location of measurement kit: Other:

5

IV – App study weekly survey



App study weekly survey full text

1. Have you been in your room for more than 30 minutes?
Yes
No

If no, questionnaire terminated with following note:
Thanks for attempting the questionnaire, please try again when you've been in your room for over 30 minutes!

2. In terms of temperature, how do you feel at the moment?

Cold
Cool
Slightly cool
Neutral
Slightly warm
Warm
Hot

3. How would you prefer to feel?

Much cooler
A bit cooler
No change
A bit warmer
Much warmer

4. At the moment, how do you find the air movement?

Very low
Low
Slightly low
Neither high nor low
Slightly high
High
Very high

5. What would you prefer to have?

Much less air movement
A bit less air movement
No change
A bit more air movement
Much more air movement

6. At the moment, how do you find the humidity?

Very dry
Dry
Slightly dry
Neither humid nor dry
Slightly humid
Humid
Very humid

7. What would you prefer to have?

Much drier
A bit drier
No change
A bit more humid
Much more humid

8. Do you find the environment:

Comfortable
Uncomfortable

9. Are the following open/closed or on/off?

Windows	open/closed
Curtains	open/closed
Heater	on/off

10. Please tick all the items of clothing you are currently wearing:

T shirt
Long sleeve top
Jumper/hoodie
Cardigan
Trousers
Shorts
Skirt
Dress
Tights
Socks
Shoes
Other:

Appendix C

Additional survey materials

Consent Form

Southampton UNIVERSITY OF

Consent form ID:

CONSENT FORM

Study title: Mayflower Halls thermal comfort study: Investigating the influence of thermal history

Researcher name: Ms. Rucha Amin
Ethics reference: 23863

Please initial the boxes if you agree with the statement(s):

I have read and understood the information sheet (V1) and have had the opportunity to ask questions about the study. ☐

I agree to take part in this research project and agree for my data to be used for the purpose of this study ☐

I understand my participation is voluntary and I may withdraw at any time without my legal rights being affected ☐

I understand that information collected about me during my participation in this study will be stored on a password protected computer and that this information will only be used for the purpose of this study. All files containing any personal data will be made anonymous.

Name of participant (print name)..

Signature of participant...

Date..

[October 2016]

Participant Information Sheet

UNIVERSITY OF Southampton

Participant Information Sheet

Study Title: Thermal comfort study in Mayflower Halls

Researcher: Ms Rucha Amin **Ethics ID:** 23863

Please read this information carefully before deciding to take part in this research. If you are happy to participate you will be asked to sign a consent form.

What is the research about?
This research study is part of a PhD project looking at the influence of 'home' climate on peoples' preferences for temperature in a new location. This is interesting aspect to study as it can have a significant effect on the energy used to provide comfortable conditions in a building. All participation is voluntary and you can withdraw at any time.

Why have I been chosen?
You have been selected as a new resident of Mayflower Halls where the study has been conducted for the last two years.

What will happen if I take part?
To take part in the study, you will be asked to:

- Conduct a face to face questionnaire (10-15 mins) in your room which will ask about your background as well as your impressions of the environment in your room. Some measurements of the indoor environment will also be taken during this time.
- Place a small (matchbox sized) temperature and humidity logger in your room for the duration of your stay at Mayflower. This will be collected at the end of the study (May 2017).
- Complete a very short survey (1 minute) once a week via an app which will be installed on your phone. You are not required to do this during vacation time or exam periods.

Are there any benefits in my taking part?
To thank you for your time, you will enter a scheme to earn **Amazon vouchers** based on the number of app-surveys you complete. The vouchers will be given upon return of the data logger installed in your room. An outline of the scheme is provided below, all incentives are given at the researcher's discretion.

- Everyone who completes all three tasks outlined above will earn a **£15 Amazon voucher.** Note: you are allowed to miss up to three weeks of the app survey and still be eligible to claim this voucher. You will be notified when you have missed two weeks and also if you are no longer eligible for the voucher.
- Anyone who completes more than the required one survey per week for at least 50% of the study duration will received a **£20 Amazon voucher.** You will be notified if you are on track to receive this voucher
- The participants with the top 5 highest number of responses will receive a **£25 Amazon voucher.**

Are there any risks involved?
Taking part in this research presents no immediate risks.

Will my participation be confidential?
Your responses will be anonymous and all data will be handled in accordance with the Data Protection Act 1998.

What happens if I change my mind?
All participation is voluntary and you are free to withdraw at any time with no legal implications.

What happens if something goes wrong?
In the unlikely case of concern or complaint, please contact Research Governance Manager (02380 595058, rgoinfo@soton.ac.uk).

Where can I get more information?
Ms Rucha Amin
Sustainable Energy Research Group
Faculty of Engineering and the Environment
University of Southampton
studentcomfort@soton.ac.uk

[October 2016] [V1]

Appendix D

App study individual profiles

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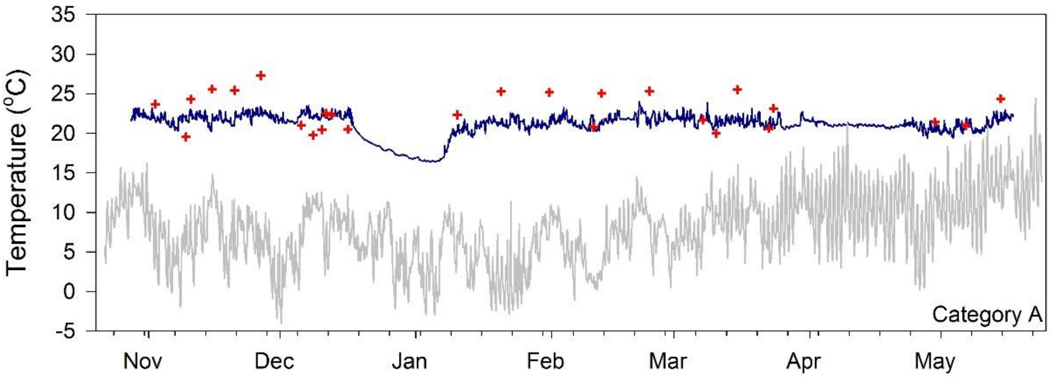

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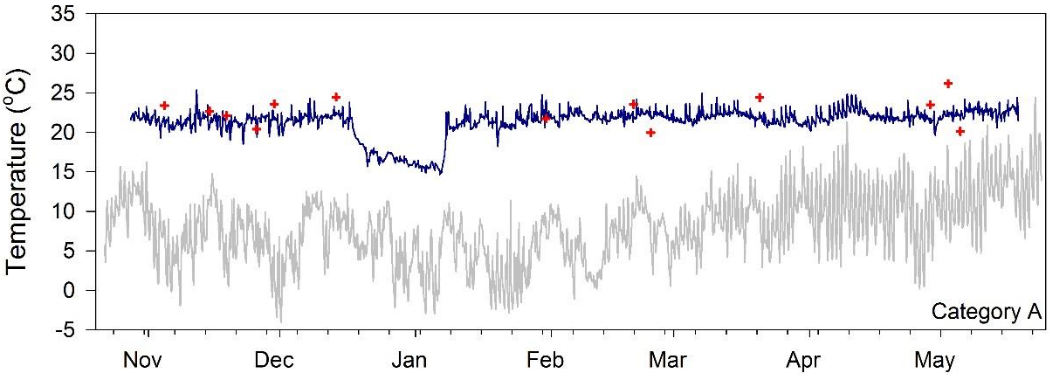
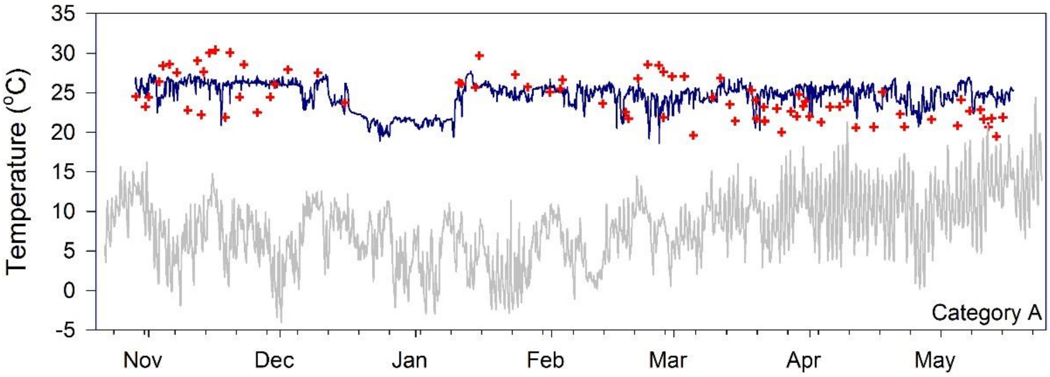


28



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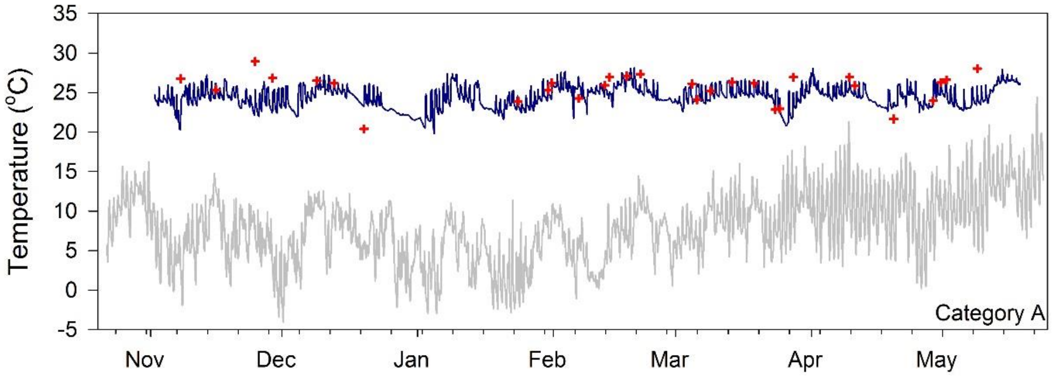
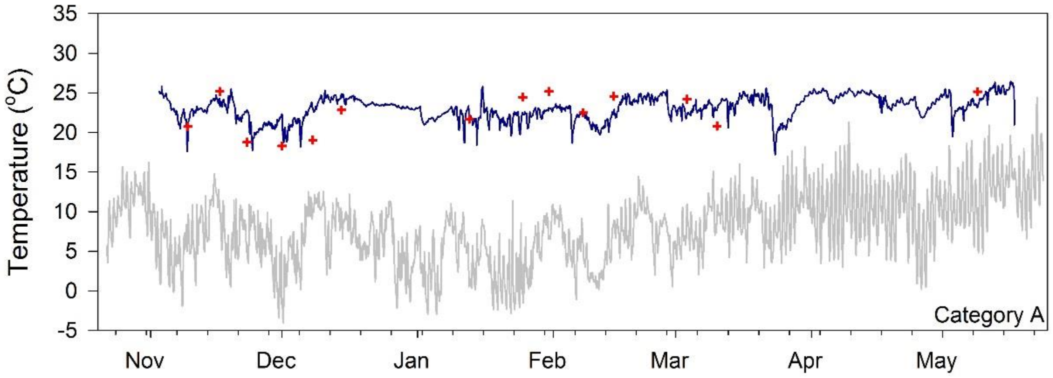


Temperature (°C)
35
30
25
20
15
10
5
0
-5
Nov
Dec
Jan
Feb
Mar
Apr
May
Category A

34



Temperature (°C)
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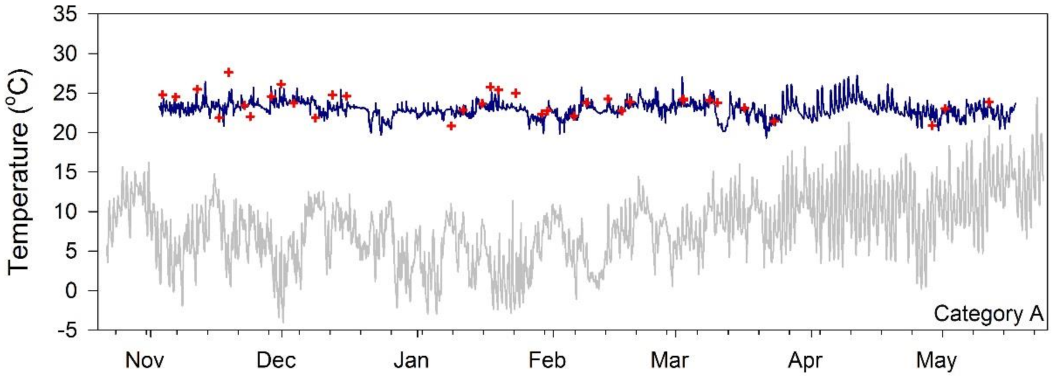
-5
Nov
Dec
Jan
Feb
Mar
Apr
May
Category A

37



Temperature (°C)
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-5
Nov
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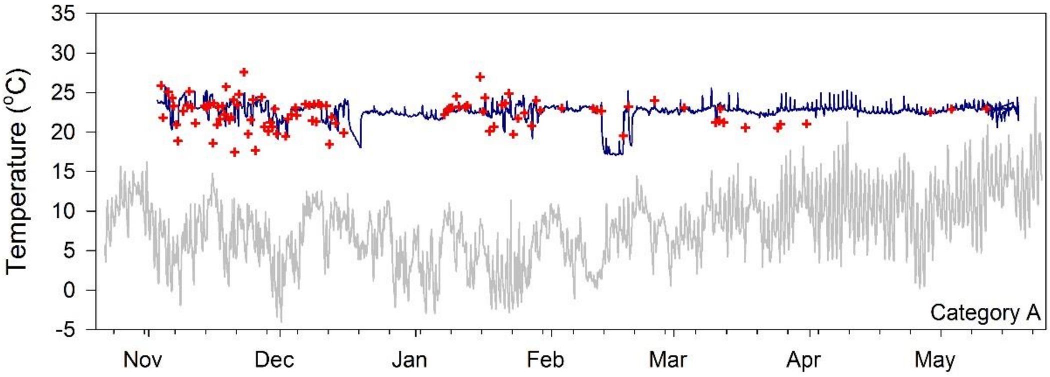
Feb
Mar
Apr
May
Category A

40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Temperature (°C)
Category A
Nov
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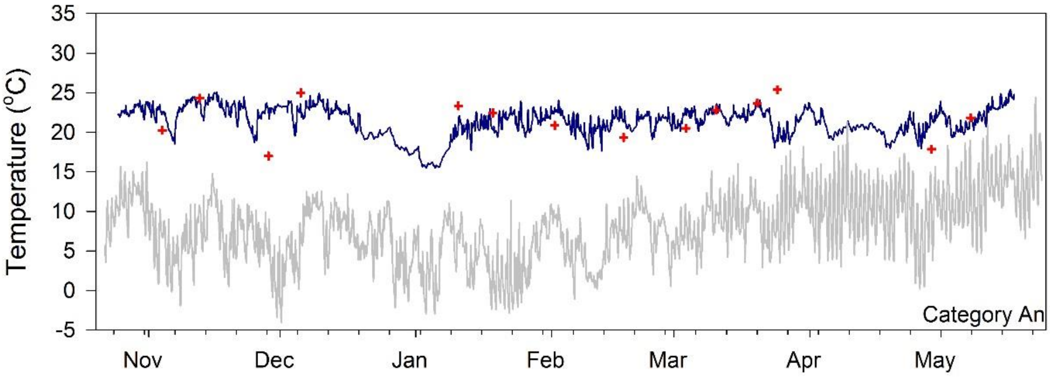
Feb
Mar
Apr
May

6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Temperature (°C)
Category An
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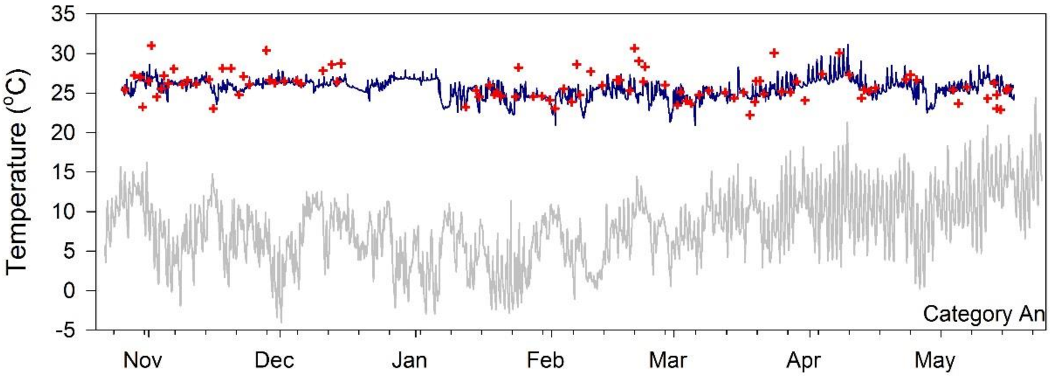
Feb
Mar
Apr
May

10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Temperature (°C)
Category An
Nov
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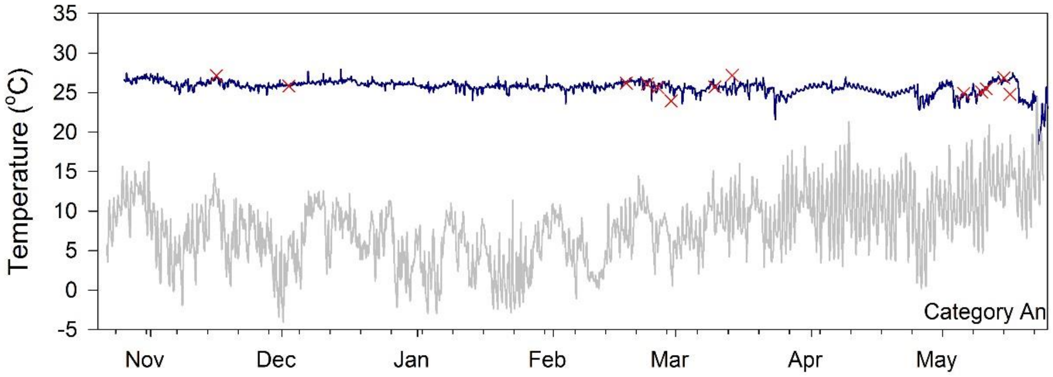
Feb
Mar
Apr
May

11



Temperature (°C)
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Category An
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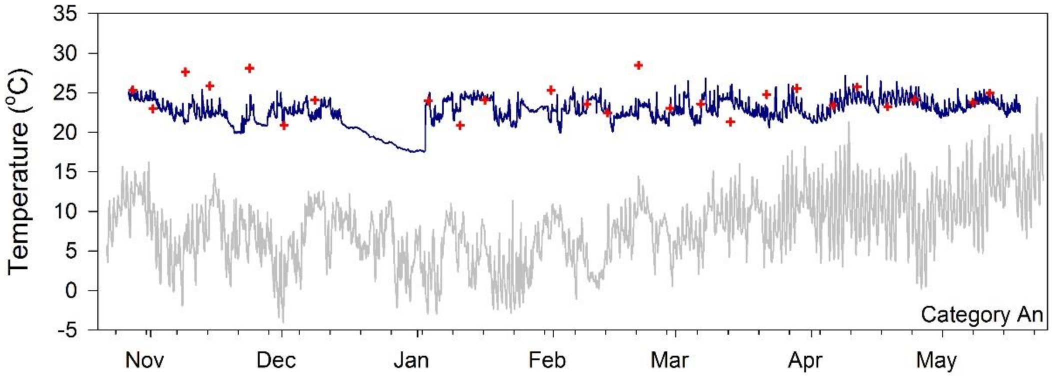
Feb
Mar
Apr
May

16



Temperature (°C)
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Category An
Nov
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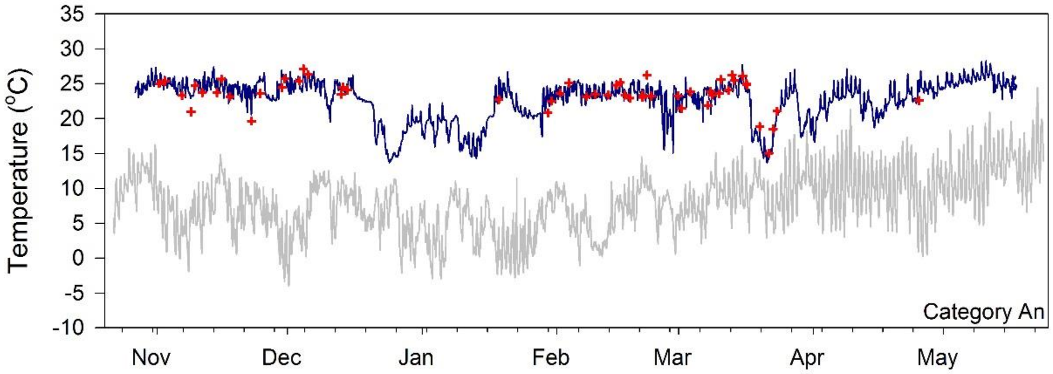
Apr
May

18



Temperature (°C)
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-10
Category An
Nov
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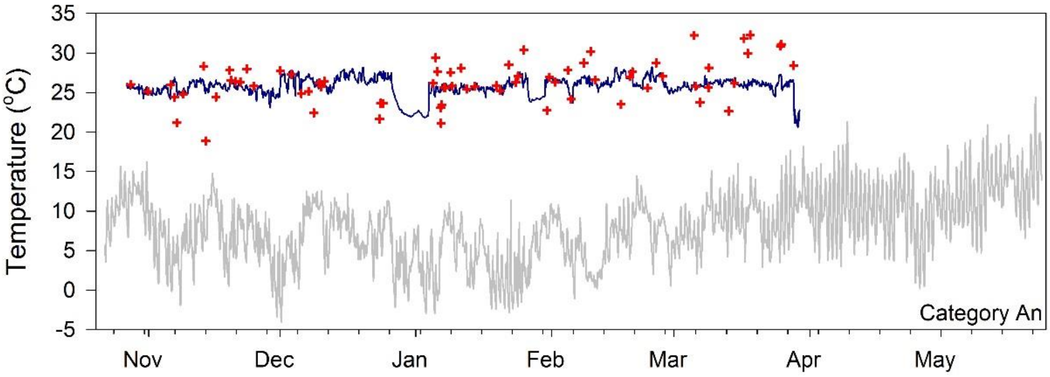
Jan
Feb
Mar
Apr
May

19



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Temperature (°C)
Category An
Nov
Dec
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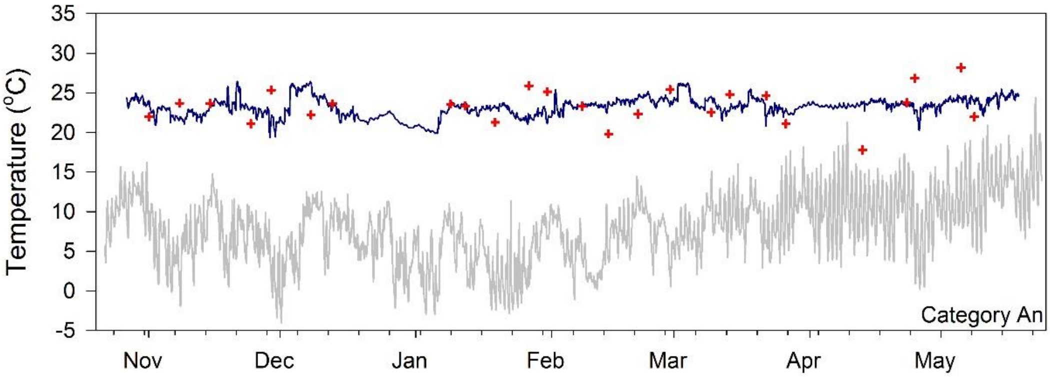
Mar
Apr
May

23



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Temperature (°C)
Category An
Nov
Dec
Jan
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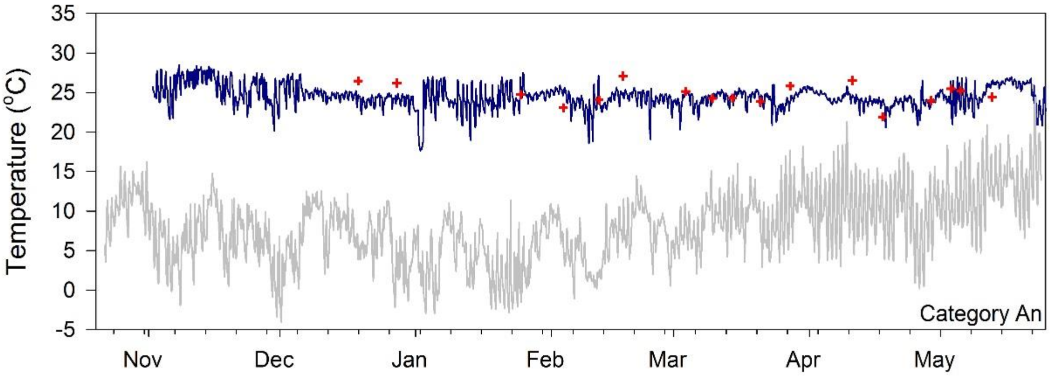
May

29



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Temperature (°C)
Category An
Nov
Dec
Jan
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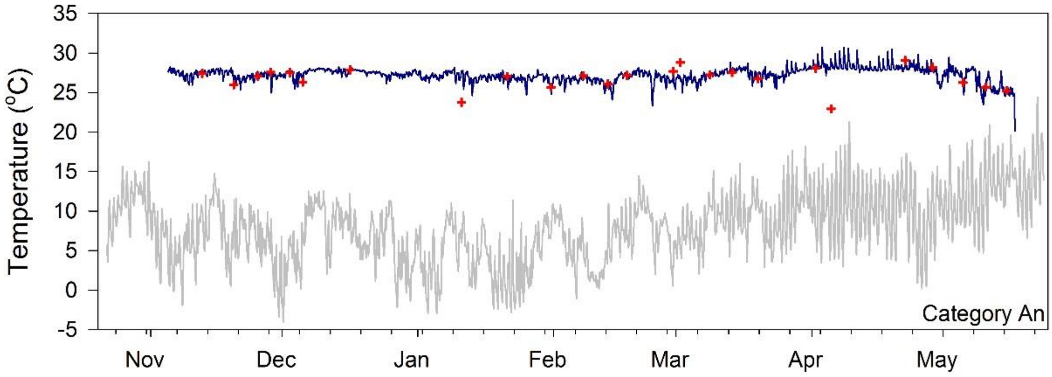
Mar
Apr
May

41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Temperature (°C)
Category An
Nov
Dec
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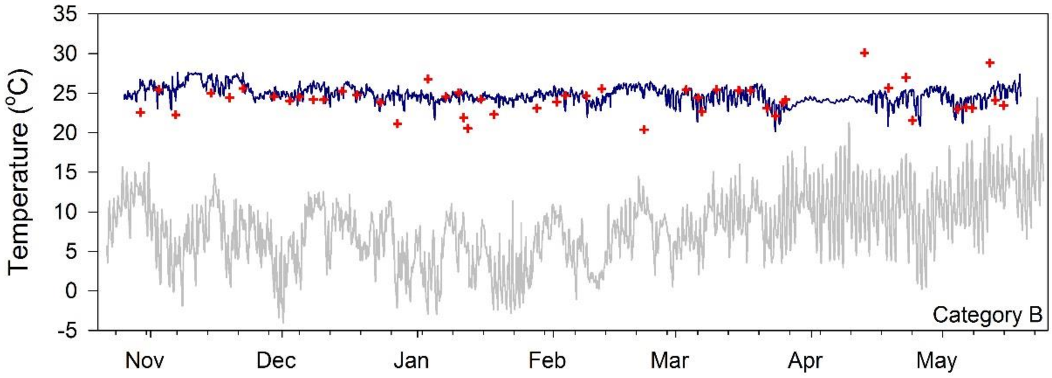
Apr
May

12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Temperature (°C)
Category B
Nov
Dec
Jan
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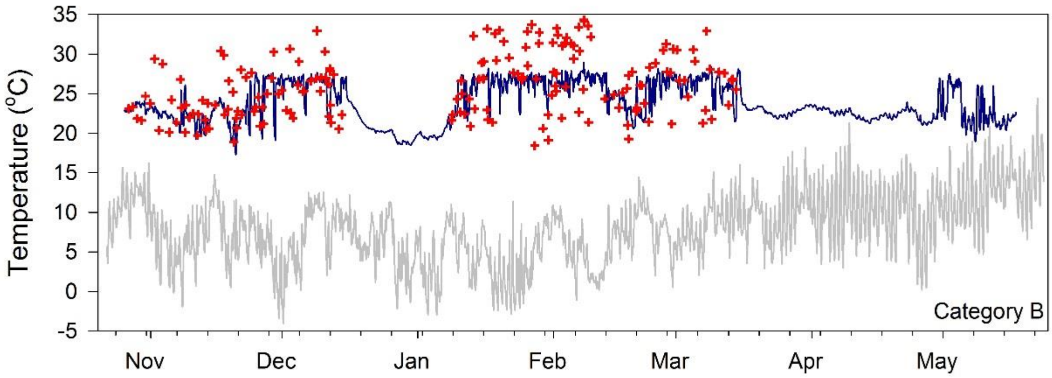
Mar
Apr
May

14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Temperature (°C)
Category B
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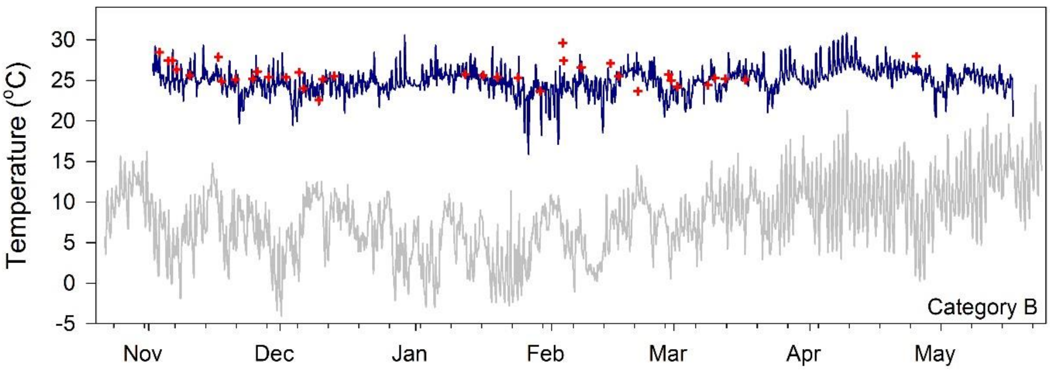
May

30


Temperature (°C)
Category B
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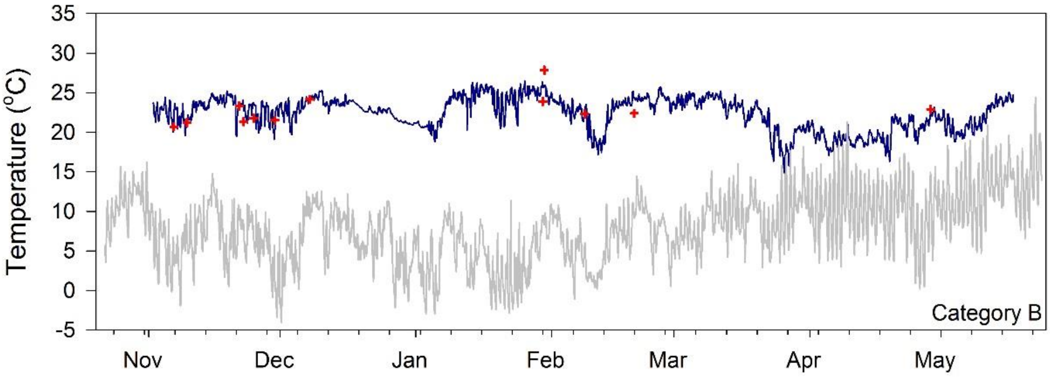
May

32


Temperature (°C)
Category B
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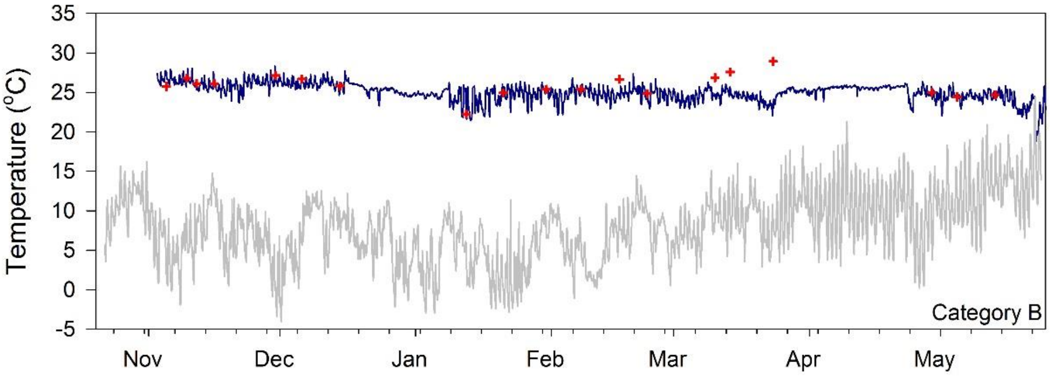
May

38


Temperature (°C)
Category B
Nov
Dec
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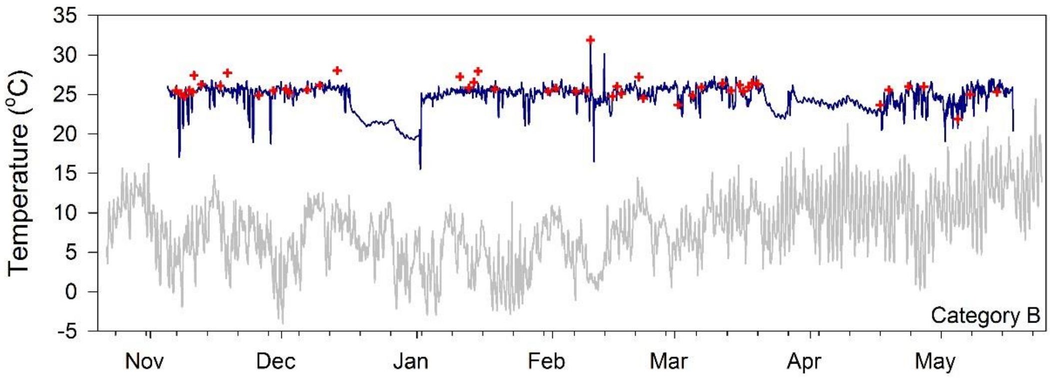
May

42



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Temperature (°C)
Category B
Nov
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May