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Thermal adaptation to high indoor temperatures during winter in two UK social housing tower blocks

Despoina Teli[1,2]*, Stephanie Gauthier[1], Victoria Aragon[1], Leonidas Bourikas[1], Patrick A.B. James[1], Abubakr Bahaj[1]

[1] Energy and Climate Change Division, Sustainable Energy Research Group, Engineering and the Environment, University of Southampton, SO17 1BJ, United Kingdom d.teli@soton.ac.uk
[2] Department of Civil and Environmental Engineering, Chalmers University of Technology, SE-412 96, Göteborg, Sweden.

Abstract

This work explores the hypothesis that exposure to high indoor temperatures during winter can change thermal expectations of the occupants, challenging the standard boundaries of thermal comfort and leading to excess in energy demand for heating. The analysis presented here is based on two case study social housing tower buildings where indoor temperatures during the heating season have been maintained at high levels for many years. Five-minute readings of air temperature and relative humidity were gathered from the lounges and bedrooms of twenty flats from February to October 2014. The measured air temperatures in the sampled period were overall much higher than the standard comfort criteria, with averages of 24.8±2.2°C for the lounges and 23.1±1.8°C for the bedrooms. Interviews were carried out with seventeen tenants in October, enquiring about their views on the indoor environment, the use of controls and their thermal sensation at the time of the survey. The results show that most people were satisfied with the temperatures in their flats, regardless of them being much higher than recommended levels most of the time. The occupants' adaptation to high temperatures could pose a great challenge to the implementation of energy use reduction strategies, if industry-based thermal criteria were to be met.

Keywords: Indoor temperature, winter, thermal history, social housing, adaptive comfort.

1 Introduction

Prediction of occupant acceptability of the indoor environment and estimation of the energy consumption associated with it relies on assumptions regarding occupant demand temperatures. Such assumptions are also used in building stock models and determine the estimated energy savings from building refurbishment, influencing governmental strategies and targets. A sensitivity analysis by Firth et al. (2010) of the primary input parameters in energy models resulted in a sensitivity coefficient of 1.55 for the heating demand temperature, which suggests that a 10% rise in the heating demand temperature leads to a 15.5% increase in the CO_2 emissions. This was significantly higher than the sensitivities of the other input parameters investigated, suggesting that heating demand temperature is the key determinant of energy use in housing.

The two widely used domestic energy calculation methodologies in the UK, BREDEM (Henderson and Hart, 2015) and SAP (BRE, 2014) use a two-zone model for space heating calculations with different demand temperatures. Zone 1 represents the living area with a typically used demand temperature of 21°C and zone 2 represents the rest of the house with demand temperature of 18°C (BRE, 2013). These values have been challenged by studies that measured lower indoor temperatures in English living rooms (Oreszczyn et al., 2006; Huebner et al., 2013; Teli et al., 2015). An extensive 2011 survey in 823 dwellings representative of the English housing stock resulted in mean room temperatures of 19.3°C for the living room, 18.8°C for the hallway and 18.9°C for the bedroom (BRE, 2013). Another study found significant variation in heating patterns with measured room temperatures ranging from 9.7°C to 25.7°C (Kane et al., 2015).

Further to the above, a historic upward trend in winter indoor temperatures has been highlighted, especially in bedrooms (Mavrogianni et al., 2013) and the 'rebound effect' from energy efficiency improvement measures has been estimated to a temperature take-back between 0.14-1.6°C due to improvements in thermal comfort (Sorrell et al., 2009). Although there is increasing measured data of indoor conditions in households, there is much less information on domestic thermal comfort compared with non-domestic buildings (Vadodaria et al., 2014) and processes that might affect comfort temperatures during winter, such as thermal adaptation, have not been sufficiently explored.

Recommended winter temperatures for living spaces

For the assessment of the indoor thermal environment of 'mechanically heated' spaces the international standards and guides recommend the use of the PMV model (ASHRAE, 2013; ISO, 2005; CEN, 2007; CIBSE, 2015). In addition, standard EN 15251 and CIBSE Guide A provide design values for winter temperatures based on PMV and assumed values for clothing insulation and metabolic rate. For living areas in domestic buildings the recommended design temperatures can be seen in Table 1. Interestingly, recently monitored temperatures in living rooms fall outside of EN 15251 Category I & II and CIBSE Guide A recommendations (BRE, 2013).

Table 1. Design indoor temperatures for residential buildings (living spaces)

	Design temperatures for winter	
	Design min (°C)	Range (°C)
EN 15251 (CEN, 2007) / 1.0 clo		
Category I[1]	21.0	21.0-25.0
Category II	20.0	20.0-25.0
Category III	18.0	18.0-25.0
CIBSE Guide A (CIBSE, 2015)		
Bedrooms (met=0.9, clo=2.5)	-	17.0-19.0
Living rooms (met=1.1, clo=1.0)	-	22.0-23.0

[1] EN 15251 categories represent different levels of expectation.

Recommended thermal criteria mainly focus on establishing minimum indoor temperatures for winter and maximum temperatures for summer, in order to avoid 'under-heating' in winter and 'overheating' in summer. The UK's 'Cold Weather Plan' recommends a minimum household temperature of 18°C for a sedentary person, wearing suitable clothing (Public Health England, 2014). However, it is stated that temperatures up to 21°C may be beneficial for health. The World Health Organisation recommends lower limits of 21°C for living rooms and 18^{o}C for bedrooms (World Health Organization (WHO), 2007; Marmot Review Team, 2011). These values are considered to be the “adequate level of warmth” in fuel poverty assessments (Department of Energy and Climate Change, 2015) and are used in energy calculations.

Upper winter indoor temperature limits are not typically provided in guidelines for the indoor environment. However, in the recent, updated version of CIBSE Guide A (CIBSE, 2015) a maximum temperature for winter is also provided for clo=1.0 and met=1.2 at 24.0^{o}C, which is recommended in order to avoid overheating. This term is rarely used to describe the indoor thermal environment in winter, when overheating can only occur due to uncontrolled use of heating. This is often considered to be a personal choice, not related to the climatic conditions or the building properties. However, the type of heating system and occupants’ interaction with building controls such as thermostats and windows can also contribute to high indoor temperatures. Winter ‘overheating’ has energy implications, which can be greater due to the possible adaptation of occupant’s thermal demand to high temperatures.

Thermal adaptation to indoor temperatures

The relationship between thermal comfort and indoor temperature has been the basis of adaptive comfort theory, with the assumption that people are able to match their neutral or comfort temperature to their indoor environment through adjustments and adaptive actions (Nicol et al., 2012). This was taken forward as a pathway towards energy use reduction, as it meant that people could adapt to lower or higher temperatures than previously assumed and therefore indoor temperature could follow an adaptive seasonal variation instead of narrow fixed comfort limits (McCartney and Nicol, 2002). On the other hand, people in air-conditioned buildings are accustomed to the narrow ranges of indoor conditions they experience, and therefore have higher expectations for ‘thermal stability’ (de Dear and Brager, 1998). Considering the above aspects of adaptation, what happens if people are exposed to high, artificially created indoor temperatures in winter?

Recent experiments in China with subjects from regions with different winter indoor temperatures highlighted the significant impacts of indoor thermal exposures on physiological adaptation and occupants’ levels of tolerance (Luo et al., 2015). A further investigation on indoor thermal history demonstrated that people who are adapted to comfortable indoor environments cannot be easily convinced to lower their expectations and accept under-conditioned environments (Luo et al., 2016). Thermal adaptation to energy-intensive indoor environments could have significant implications for future indoor temperature trends and corresponding energy use to achieve them.

The hypothesis is that changes in thermal expectation, behaviour and acclimatisation may not only apply to narrower indoor temperature ranges, but also to the indoor temperature levels people are exposed to. This paper explores whether warm indoor conditions during winter have a similar adaptation effect as stable air-conditioned environments in the summer. To investigate this question, this paper is focused on a case study social housing building where indoor temperatures during winter have been maintained at high levels for several years, due to a combination of communal electricity charges, building management, lack of understanding of heating controls and sedentary lifestyles. This paper explores the implications from the building occupants’ exposure to increased warmth during winter.

2 Case study buildings

A case study approach is used to analyse occupant response to high indoor temperatures during winter. The buildings used are two identical social housing tower blocks (Figure 1) located in the central Portsea Island area of Portsmouth, UK, owned and managed by the local authority Portsmouth City Council (PCC). The buildings were constructed in 1966 using precast prefabricated concrete panels and have 17 storeys with the same layout, including one and two bedroom apartments of 50m^2 and 70m^2 respectively. The flats are distributed along a central corridor and orientated towards East or West, at a slight angle (5^o from North). Exterior walls have an estimated U-value of 1 W/m^{2}K and the double-glazed windows which replaced the initial single-pane windows, have a U-value between 2.5-3 W/m^{2}K. Overall, the building fabric's thermal performance is poor and does not comply with the current, much stricter regulations for new constructions.

Figure 1. One of the two identical 17-storey tower blocks (left) and a storage heater in one of the flats (right).

Heating in the buildings is electrical, managed and mostly paid by Portsmouth City Council, with a small charge to the residents through the rent. Initially, the buildings were fitted with underfloor heating. However, due to system failure and maintenance issues, storage heaters were retrofitted in most flats. Therefore, there are flats in the buildings with storage heaters, others with a combination of both and flats with mainly underfloor heating. In most flats heating units are installed in the living room and hallway and approximately 40% have one also in the bedroom. Storage heaters are meant to be used under the 'Economy 7'-tariff, being charged during the night when lower electricity prices are offered by supply companies, and gradually releasing heat during the day. However, this is not the case for the tower blocks where additional charging, and consequently heat release, takes place during the day. This is due to complaints from residents whose homes have underfloor heating, which led to daytime provision of electricity for heating by the City Council resulting in high heating costs. As an example, for the year 2014 which had a winter 28% warmer than the average, the average electricity consumption for heating per flat was approximately 4,400 kwh/yr (or 74 Kwh /m^2 yr), which is 23% higher than the typical designed residential heating load (BSRIA, 2011).

3 Methodology

The indoor environment conditions, air temperature (T_a) and relative humidity (RH), were monitored in twenty-one flats within the two social housing buildings from February to October 2014. The contact details of forty-five residents were provided by Portsmouth City Council (PCC) as potential participants, shortlisted so as to achieve a good distribution of floor levels, orientations and flat types. From the 45 residents that were contacted by phone, 30 answered, 23 agreed to participate and 21 returned valid data.

Small data loggers (MadgeTech RHTemp101A) were placed in the living room and bedroom of each flat, configured to take readings at a frequency of 5-minute intervals. These data loggers follow the requirements of ISO 7726 (2001); the accuracy of the reading for the temperature is $\pm 0.5^{o}$C and the relative humidity calibrated accuracy is 3%. The data loggers were positioned so as to minimise direct exposure to solar radiation or the heating system and to avoid any disturbance to the occupants.

Interviews were carried out with seventeen of the tenants at the end of the monitoring period (October 2014). The interview questionnaire consisted of two parts, one asking about the occupants' general views on the indoor environment and their responses to it with the use of controls and the second part asking about their thermal comfort perception at the time of the survey.

Part 1- General evaluation

a) Assessment of the general conditions during winter and summer, in the bedroom and in the living room, on a 7-point scale from dry to humid, warm to cold, quiet to noisy, light to dark, stuffy to draughty.

b) Use of controls, i.e. operation of heaters and heater control settings, frequency of window opening, use of secondary heating sources or fans.

c) Temperatures considered as comfortable in winter and summer.

d) General satisfaction with the flat in terms of temperature, noise, daylight, air quality.

e) General questions: hours spent in the flat, room mostly used during the day, number of people in the household, age group and gender.

Part 2- Comfort conditions at the time of the survey

a) Thermal sensation vote on the ASHRAE 7-point scale (cold, cool, slightly cool, neutral, slightly warm, warm, hot)

b) Thermal preference vote on a 5-point scale (much warmer, a bit warmer, no change, a bit cooler, much cooler)

c) Overall comfort assessment on a 5-point scale from very comfortable to very uncomfortable.

d) Clothing level using a list of garments.

The interviews took place on the 1st and 2nd of October with outside average daily temperatures of 17.9^{o}C and 15.5^{o}C respectively and average daily relative humidity of about 90% (Gosport Weather, 2015). The heating was turned on by the City Council on the 25th of September after residents' request. The recording of indoor air temperature (T_a) and relative humidity (RH) continued during the interviews to enable comparison of occupants' thermal sensation responses with the indoor environmental conditions at the time of the survey.

4 Results and discussion

Based on the interview responses, residents had lived in their flats for a period between 1 and 16 years until the time of the interview and therefore all of them had experienced the indoor climate of their home for a considerable time. The average reported time spent at home is 18 hours ± 4, with most respondents spending their entire day inside the building. Therefore, participants' lifestyle is overall characterised by low activity levels and minimal exposure to outdoor climatic variations.

Indoor air temperature

The data loggers were placed in different types of flats, including both one-bedroom and two-bedroom flats, different floors, orientations and capacity of heating units. Using inferential tests, relationships between measured indoor temperatures and the above parameters were carried out in order to investigate their influence on the indoor thermal environment. No statistically significant relationship was found, suggesting that other parameters may have an influence on the indoor demand temperature.

The average measured air temperature in the investigated heating period (mid-February to early-April) during occupied hours was 24.8^{o}C (σ=2.2) for the lounges and 23.1^{o}C (σ=1.8) for the bedrooms. The occupied period used for the lounges is between 07:00 and 23:00 and for the bedrooms 23:00-07:00, based on occupants' responses to the interviews. This is an approximation as most residents do not have a fixed daily schedule, however they spend most of their day at home.

The air temperature distribution per room can be seen in the boxplots of figures 2 (lounges) and 3 (bedrooms). Temperature ranges were overall at much higher levels than the minimum acceptable winter temperatures of 21^{o}C for lounges and 18^{o}C for bedrooms (World Health Organization (WHO), 2007) and the CIBSE recommended for comfort of 22-23^{o}C for lounges and 17-19^{o}C for bedrooms (CIBSE, 2015). The occupants' general thermal evaluation of their lounge and bedroom is also illustrated in figures 2 and 3. Seven of the interviewees assessed their lounges' thermal environment as 'OK', whilst four assessed it as 'a bit cold', 'quite cold' or 'too cold' even though the average air temperature was above 25^{o}C (see Figure 2). Only four interviewees considered their lounge to be 'quite warm' in winter and two as 'too warm'. Two cases worth special consideration, flats 19 and 20. The resident of flat 19 characterised his lounge as too warm during winter even though the measured air temperature range is near the lower recommended limit. This person reported spending an average of 12 hours at home (including sleeping time), much less than most of the other interviewees. He was one of only two of the interviewees that work and spend considerable time outdoors and in different indoor environments. Therefore, his thermal experience and activity level is very different to the others'. On the other hand, the resident of flat 20 has one of the warmest lounges and yet evaluated it as being 'too cold' during winter. This participant is an elderly resident (88 years old, the oldest participant) and therefore health condition, reduced activity level and physiology may have strongly influenced her thermal sensation.

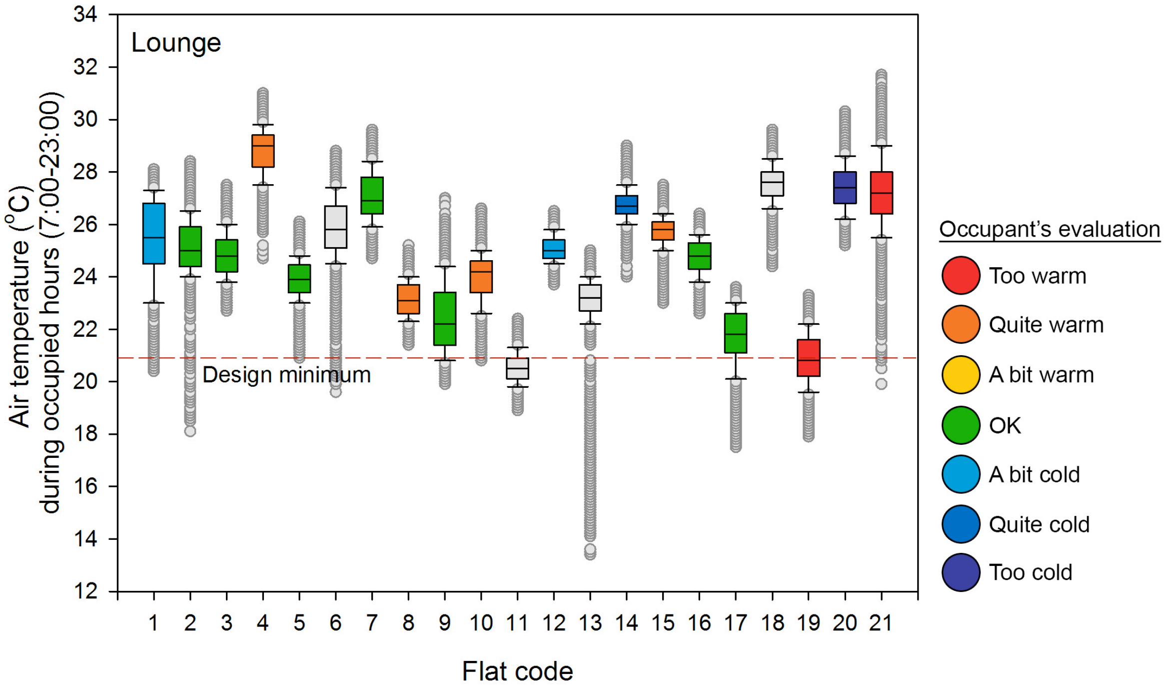

Figure 2. Air temperature box plots in the monitored lounges between 07:00 and 23:00 in the investigated heating period, with occupants' thermal evaluation (grey fill: no interview given). Box: the 50% of the measured air temperatures; whiskers: the 10th and 90th percentile; dots: outliers; black line: median.

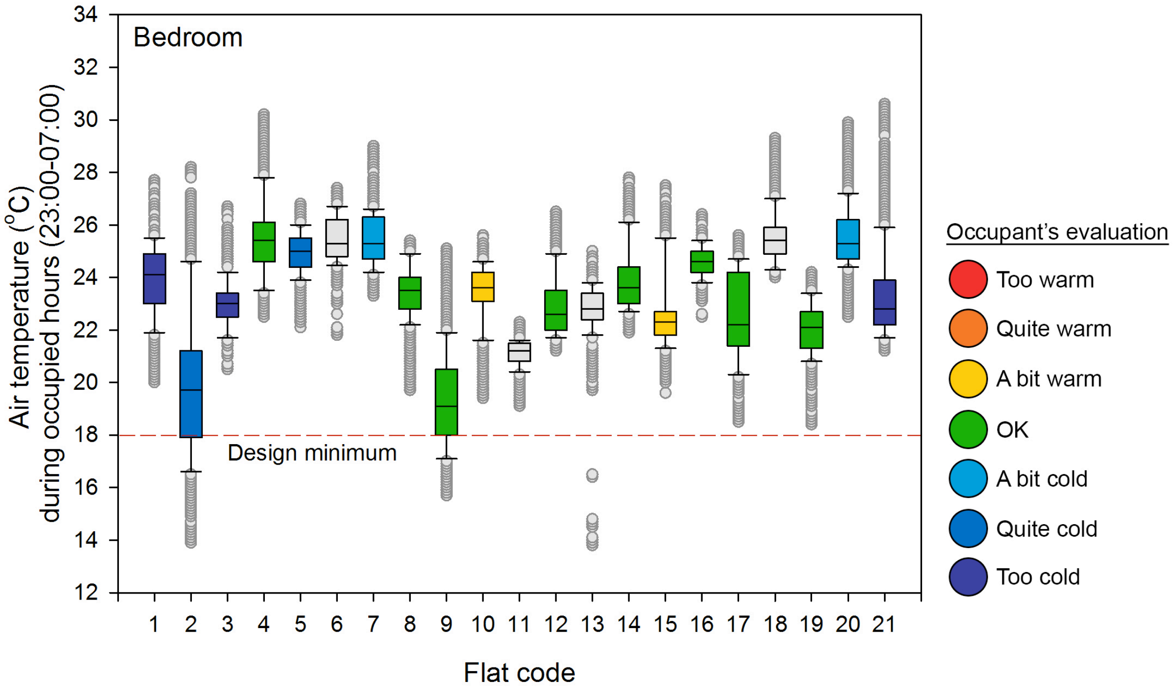

Figure 3. Air temperature box plots in the monitored bedrooms between 23:00 and 07:00 in the investigated heating period, with occupants' thermal evaluation (grey fill: no interview given). Box: the 50% of the measured air temperatures; whiskers: the 10th and 90th percentile; dots: outliers; black line: median.

Figure 4 shows the measured air temperatures in the 21 lounges during the two days with the highest diurnal variation (12th and 13th of March 2014). Meteorological data were provided by Gosport weather station (Gosport Weather, 2015), which is located 2 km west of the case study buildings. As can be seen in the temperature profiles of Figure 4 there was little variation of the indoor air temperature, even with diurnal change of up to 10°C. The occupants clearly experience both high and relatively constant temperatures, in a similar way as people in air conditioned spaces are exposed to narrow temperature ranges. Based on the adaptive comfort principle, such exposures create expectations, which can be expected to happen regardless whether the narrow ranges refer to cooled or heated spaces (de Dear and Brager, 1998).

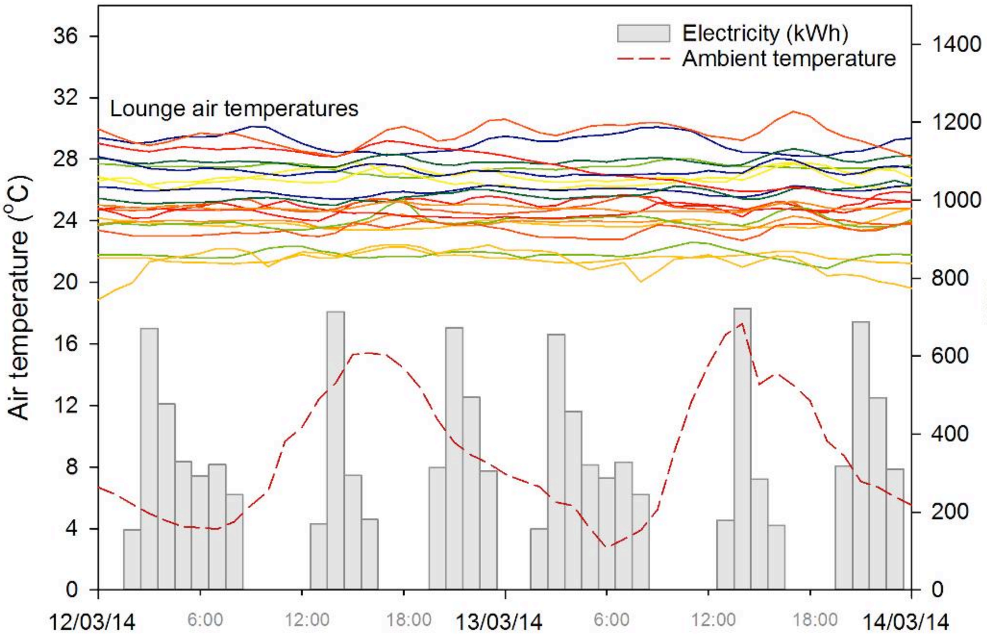

Figure 4. Measured hourly air temperature in the 21 lounges against the external ambient hourly temperature and the electricity consumption for heating in two days in March 2014. Weather data from Gosport weather station (Gosport Weather, 2015).

The average measured air temperature for the lounges in the summer period (June to mid-September) during occupied hours was 23.9°C, which is 1°C lower than the corresponding winter average temperature. The average measured summer air temperature for the bedrooms during the occupied night hours was 23.8°C, only slightly higher than the average in winter. Therefore, occupants experience on average warmer conditions in winter than in summer. This probably explains why the majority of interviewees assessed their thermal environment in summer as ‘OK’ and only two found their lounge and bedroom as ‘too warm’. Overall, the occupants did not express any concerns for uncomfortably high indoor summer temperatures, although air temperatures of up to 31°C were registered during the monitoring period.

Use of heating controls

The interviewees were asked about how frequently they use the available heating controls (ON/OFF, ‘input’, ‘output’). The ‘input’ setting regulates the amount of heat to be stored during the night, whilst the ‘output’ setting regulates the amount of heat the storage heater gives off. In the case of manual models, such as those in the case study buildings, the settings should be adjusted with the weather and daily requirements. As can be seen in figure 5, most respondents never use the available controls.

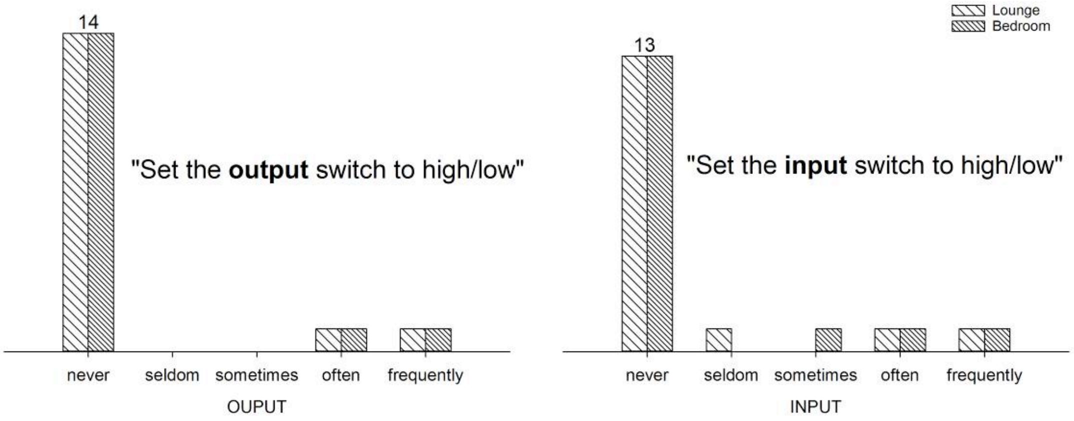

Figure 5. Frequency of use of storage heating switch controls.

With the residents' permission, the settings on all storage heaters at the time of the interview were recorded and then reviewed across 5 categories from low to high. As can be seen in Figure 3, the majority of heaters were set to 'high' and 'medium high' on both 'input' and 'output', even though it was only the beginning of the heating season (1st October). The majority of the respondents, 63% and 75%, reported that they never used the 'ON/OFF' switch of the heaters in the lounge and bedroom respectively and reported that they kept it constantly on. This differs significantly to the situation encountered in a nearby social housing tower block previously studied, where occupants pay their bills separately and preferred to switch the storage heaters off due to the increased costs incurred (Teli et al., 2015). This comparison highlights two issues: a) the lack of engagement with controls due to a lack of financial motivation to do so and b) the risk from changing the billing conditions in the case study buildings without first improving the building's thermal performance. This could lead to under-heated homes and fuel poverty, similar to the nearby tower block. Given the occupants' adaptation to high indoor temperatures, the implementation of such changes would be even more challenging.

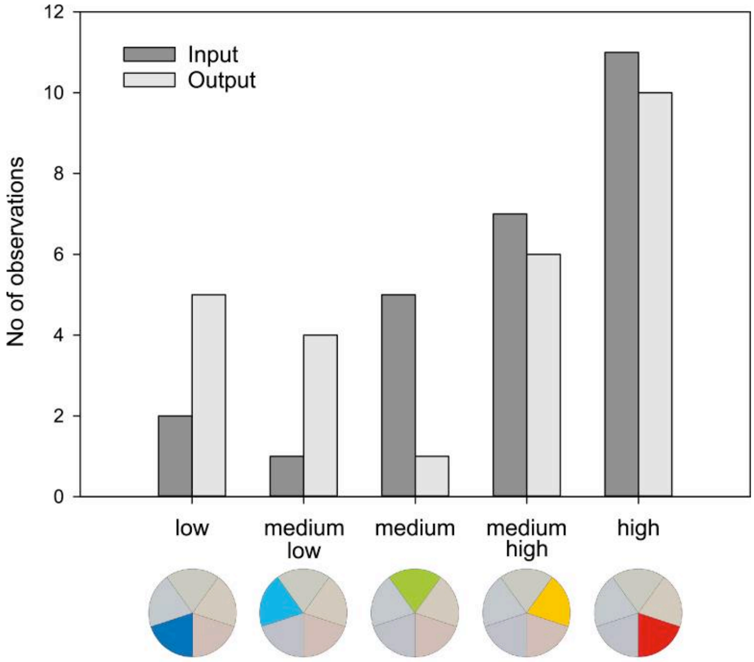

Figure 6. Observed settings during the interview visit.

Comfort conditions

Based on the adaptive comfort principle that people make adjustments in order to feel comfortable at the temperatures they typically encounter (Humphreys et al., 2016), the subjects in this study are expected to have adjusted their clothing to the high indoor temperatures they experience. The calculated clothing insulation values of the residents during the interviews support this, as the average value was 0.52 clo ±0.17, much less than the typically assumed 1 clo for winter (Table 1). The average air temperature during the 17 surveys was 24.0^{o}C ±1^{o}C.

The majority of interviewees are over 55 years old but their age is not expected to have influenced their comfort conditions as research has found that at a given activity and clothing level older people preferred the same thermal environments as younger people (Collins and Hoinville, 1980; Langkilde, 1979). Elderly people are vulnerable due to their lifestyle which involves low activity and high risk related to poor thermoregulatory responses (Parsons, 2014). However, their preferred temperatures have been found to be similar to those of young adults (Parsons, 2014).

The residents' neutral (comfort) temperature was calculated from their thermal sensation vote (TSV) and the indoor operative temperature at the time of the survey (T_{op}), using the equation $T_{comf}=T_{op}$-TSV/b (Humphreys et al., 2007). As the radiant or globe temperatures were not measured in this study, the air temperature is used instead of the operative temperature. This should not affect the findings, given the overcast conditions during the interviews, the mild outdoor temperatures and the concrete construction of the buildings. Constant 'b' expresses the sensitivity of people to thermal changes and has been estimated through analysis of extensive survey data at 0.5K (Humphreys et al., 2013).

Figure 7 shows the calculated comfort temperature per interviewee, against the mean air temperature in the interviewee's lounge during occupied hours in the heating period. Thirteen of seventeen respondents reported a neutral thermal sensation during the interview, leading to a strong correlation of their comfort temperatures with the mean temperature they experience in their lounge (black dots in Figure 7). Eleven of them had a 'no change' preference, whilst two preferred 'slightly cooler', which is still within the comfort range. Four cases (red dots in Figure 7) reported a warm thermal sensation during the interview, resulting in lower comfort temperatures. However, from these 4 respondents, one had a 'no change' preference and the other three preferred only 'slightly cooler'. Therefore, their warm thermal sensation vote does not necessarily indicate discomfort. The average comfort temperature of the 17 respondents with consistent thermal sensation and preference votes at the time of the survey was 23.8^{o}C ±1.3^{o}C, whilst including the four interviewees with low comfort temperatures brings a mean comfort temperature of 22.8^{o}C ±2.5^{o}C.

For comparison, the predicted mean vote (PMV) was also calculated for each respondent using the measured air temperature and relative humidity, the clothing insulation as estimated from the questionnaire's checklist and the following assumptions: 1) a metabolic rate of 1.1 MET 2) a low air velocity of 0.5 m/s and 3) $T_a=T_{op}$. The PMVs ranged between -1.3 and 0.4, with an average of -0.4. Overall, the PMV lied mainly to the cold side of the scale due to the low clothing level of the subjects.

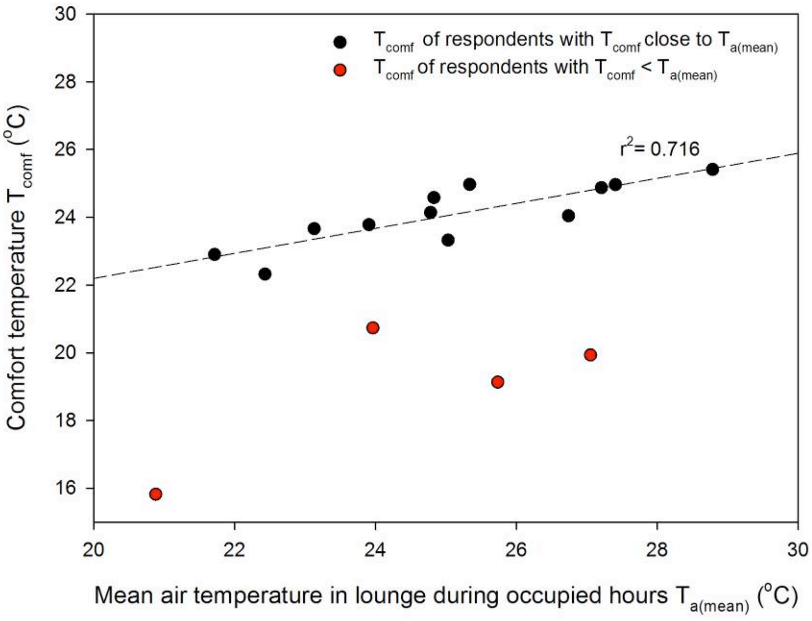

Figure 7. Calculated comfort temperatures for each interviewee, against the mean air temperatures in the lounge during occupied hours in the investigated heating period.

5 Conclusions

This paper presents results from a case study on the influence of thermal exposure to a particular indoor environment on occupants' comfort conditions. The analysis presented demonstrates that increased indoor temperatures combined with a sedentary lifestyle and minimal exposure to outdoors, or other variable thermal environments, may lead to a high level of thermal adaptation to these high temperatures. This poses a challenge to the standard boundaries of thermal comfort, leading to excess in energy demand for heating. The results suggest that thermal comfort research should look into incorporating indoor thermal history in predictions of occupant neutral temperatures.

The thermal sensation votes and the interview responses showed that most people were satisfied with the temperature in their flats both in winter and summer, regardless of being at much higher temperature than recommended levels most of the time. The results suggest that the residents have gone through behavioural and psychological adaptation, and possibly physiological acclimatisation due to warm exposure.

From this study, it can be inferred that occupants' adaptation to high temperatures would challenge the implementation of energy use reduction strategies, if industry-based temperature design criteria were to be met, as these would conflict with the occupants' 'adapted' comfort temperatures. On the other hand, the participants did not highlight issues of summer discomfort, even though measured temperatures were high, which suggests that their heat acclimatisation may have contributed to higher tolerance during summer. These findings highlight the significance of controlling the indoor environment, as high indoor temperatures do not only have direct effects, such as the instant increase in energy use for heating. On the long run, exposure to high indoor temperatures can lead to high comfort temperatures, which would have a long-lasting and challenging effect.

There are limitations in this study that should be noted, such as the small sample size (21 flats and 17 interviewees), the lack of more detailed information on characteristics of the participants that may have affected their thermoregulation (health, weight and height), the lack of a control group and of more detailed thermal comfort surveys. However, the extensive environmental monitoring and the face-to-face interviews have helped to highlight significant patterns, as discussed in the paper and highlighted above. Overall, the findings point to the need for further research to investigate the hypothesis introduced here.

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