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Summertime temperatures in 282 UK homes: thermal comfort and overheating risk

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Abstract

Summertime temperatures in UK homes are a matter of increasing concern, particularly because of global warming and an increased incidence of heat waves. Refurbishment adds to uncertainty about the resilience of UK homes to climate change. This paper examines internal summertime temperatures in the living and bedrooms of 282 homes in the UK city of Leicester. This is a statistically representative sample of the city's housing stock. The generally cool monitoring period included a short period of hot weather. Occupant behaviour had a significant impact on internal temperature, 13% of the homes were actively heated even during the spell of hot weather. In the 230 unheated homes, 28% of the living rooms and 88% of bedrooms were classed as severely overheated, as judged by the static, CIBSE, criteria. In contrast, 64% of the living rooms and 71% of the bedrooms were judged uncomfortably cool as defined by the BSEN15251 Cat II adaptive thermal comfort standard.

Comfort, houses, UK, measurement, summer.

Introduction

Summertime temperatures in homes are of increasing concern, even in the relatively mild climate of the UK because very high indoor temperatures can be life threatening and are likely to occur more often as global temperatures rise. Whilst elevated temperatures can be overcome with air conditioning, this would simply increase electricity use and be, for the UK at least, a new source of greenhouse gas emissions. Thus there is interest in understanding what summertime temperatures are in UK homes and the effect of location, house type and construction and occupant behaviour on these temperatures.

The European heat wave of 2003 has been particularly closely studied. This heat wave, which was most intense in the UK in August, is estimated to have caused an additional 2045 deaths in the UK (ONS, 2003) with as many as 70,000 excess deaths between June and September, across Europe as a whole (WHO, 2007). The most vulnerable were the elderly, especially those over 75 and living alone. South facing upper floor flats also tended to increase overheating risk (NHS, 2011). Using mortality data for the Greater London region, Hajat et al (2002) showed that an average daily external temperature over 19°C seems to lead to an increase in heat related deaths. The rate of increased deaths was related to the degree to which the three day moving average external air temperature exceeded the 97th centile value[1]. The use of a moving average temperature enables hot spells rather than isolated hot days to be identified. It also corresponds rather well to the way that indoor temperatures change with ambient conditions; they tend to be influenced by the external temperature over the recent past rather than the instantaneous external temperature. The use of a locally defined

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[1] In London the 97th centile value of the three day moving average temperature from 1976-96 was 21.5°C.

threshold, i.e. the 97th centile value, suggests that deaths due to a heat wave will be fewer in areas that are generally warm, like the south east of England, than if a heat wave of the same intensity and duration hit a region that is generally cooler, such as the more northerly areas of England.

Internal temperatures during the 2003 heat wave were measured in five London flats and four homes around Manchester (Wright et al., 2005). The heat wave lasted 9 days in Manchester and 12 days in London. In Manchester, the external temperature reached 32.1^{o}C and in London 37.4^{o}C. In both locations, the daily average external temperature was always above 20^{o}C, except for one day in Manchester. In Manchester the living room of one home reached 30^{o}C and one of its bedrooms 36.0^{o}C, and a London flat 37.9^{o}C, which is, of course, dangerously high.

Whilst the summer of 2003 was very unusual, according to current climate projections, similar extreme weather events will take place every two or three years by the 2050s (Mayor of London, 2008) and by the 2080s, such temperatures would be considered unusually cool (Eames et al., 2011). There is therefore interest in knowing the extent to which UK homes should be adapted to withstand higher summertime temperatures and whether adaptation is necessary in all geographical areas. One obvious adaptive measure is to install air-conditioning, but this would simply increase summertime energy demands and hinder progress towards a low-carbon future. The UK National Health Service has produced a heat wave plan which contains advice on coping with such extreme weather events and public heat wave warnings are issued (NHS, 2011).

Modelling studies, for example by Hacker et al. (2008), have shown that thermal mass and controlled ventilation can much improve summertime thermal comfort. In a thermally massive home in the London region, bedroom temperatures were predicted to become excessive in the 2080s, but in a lightweight home overheating was predicted to set in as early as the 2020s. Similarly, Peacock et al. (2010) have shown that solid masonry wall homes are more comfortable in summer than thermally lightweight dwellings, which, in the London region, become uncomfortably hot by the 2030s. The ability to maintain bedrooms at a comfortable temperature was noted as being of paramount importance in understanding overheating risk. Mavrogianni et al. (2012) studied the impact of energy efficient refurbishment on the internal temperatures of homes in London. They noted that retaining exposed thermal mass and the ability to ventilate effectively would enable mean and peak internal temperatures to be controlled up to the 2050s, but internal insulation that masked thermal mass led to increased internal temperatures.

Although modelling studies are extremely useful, it is difficult to capture credibly the full variability of occupant behaviour and house construction, geometry and ventilation potential. In contrast, measurement can capture such diversity and, if the study is large enough, also relationships between those that are vulnerable to elevated temperatures, such as the elderly, sick and the very young, and the homes in which they live. There are, however, few large UK studies of summertime temperatures in homes; most large-scale studies have focused on winter temperatures[2]. The energy follow-up survey commissioned by the UK Department of Energy and Climate Change in 2010, to supplement the data from the English housing survey, could help fill this gap.

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[2] This is not surprising as in the UK wintertime space heating energy demands are a major source of greenhouse gas emissions and under heating of homes is a significant health risk. Such studies include, for example, 1600 homes of those in fuel poverty monitored (Oreszczyn et al., 2006), 427 homes in the CaRB study (Shipworth et al., 2009), 14 low-energy homes monitored in Milton Keynes (Summerfield et al., 2007) and 25 households in Northern Ireland (Yohanis et al., 2010). The most extensive field survey (Hunt & Gidman, 1982) measured spot temperatures in each room of 100 homes in February and March 1978.

This paper also contributes to filling this gap, and is, to the authors' knowledge, the first reported large-scale study of summertime thermal comfort in UK homes. It presents an analysis of the internal temperatures recorded in 282 homes in the UK city of Leicester. Assessments are made using established overheating criteria and an adaptive model of thermal comfort. Comparisons are made with temperatures recorded during the 2003 heat wave and significant relationships between thermal comfort and overheating risk and house type, construction and occupancy are highlighted.

Household survey and temperature measurements

Leicester was the case study city chosen by the 4M project consortium that was concerned with the determination of city carbon footprints (Lomas et al., 2006). Leicester is geographically central in England and has a clearly identifiable boundary with the surrounding rural area (Fig. 1). With a resident population of 280,000 in 2007, living in over 111,000 homes (ONS, 2010), Leicester is the UK's 15th largest city and has households that cover a wide range of socio-economic categories, from affluent to the most disadvantaged.

The most frequent housing types are semi-detached dwellings (37% of the city's housing stock) and terraces (35%), which proliferate towards the city centre along with flats (17%). The detached houses are found primarily in the suburbs (10%) (ONS, 2010). Over the years, many homes have been made more energy efficient using insulation and modern boilers and controls.

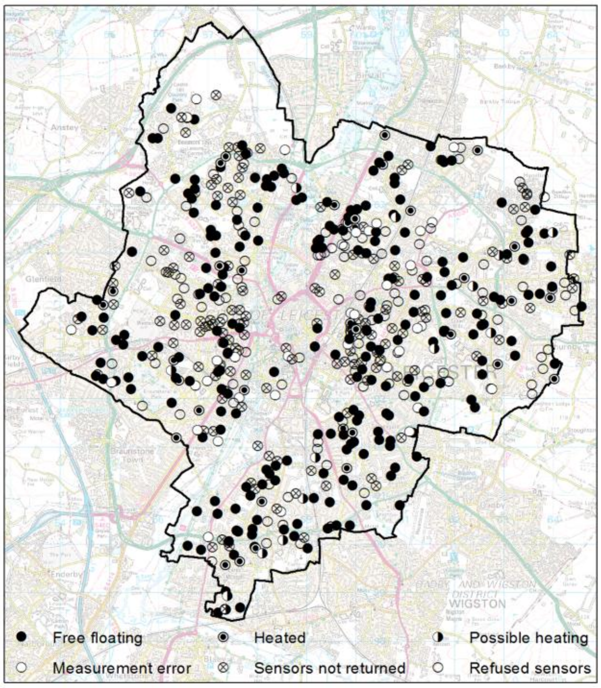

Figure 1. Leicester and the households surveyed: the 282 darker dots indicate those for which useable temperature data was obtained.

One aim of 4M was to measure domestic energy use, travel behaviour and garden management practices. To do this, a face-to-face computerised questionnaire was administered at 575 homes (i.e. 0.5% of Leicester homes). These were randomly selected after stratifying by percentage of detached homes and percentage with no dependent children (Fig. 1), which is important here as the thermal comfort of the elderly is of interest[3]. The questionnaire was devised by the 4M team and conducted on their behalf by the National Centre for Social Research (NATCEN) between 17th March and 18th June 2009. Relevant to this work, the survey captured the house type[4], the number of occupants, the age of the oldest occupant, the age of the house, whether the loft or walls were insulated or not, and the mode of tenure. The responses of the interviewees were recorded directly onto a laptop and then downloaded, cleaned and organised in the 4M database. The 4M Living in Leicester (LiL) survey provides a consistent and comprehensive data set about households, their home energy

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[3] The data points bear no direct relationship to the households surveyed but preserve the number and rough location of those interviewed.

[4] Aerial imagery was used to confirm these responses.

demand, travel behaviours and garden management practices. It is the first such data set collected in the UK and has been exploited for a number of purposes.

As part of the LiL survey, Hobo pendant-type temperature sensors (Fig. 2) were used to record internal temperatures over an eight-month period beginning on 1st July 2009. The primary purpose was to capture the internal temperatures during the winter heating season (Kane et al., 2011). The sensors take a spot measurement of temperature on each hour point. They were calibrated by the manufacturer and found to be accurate to ±0.4°C (Tempcon Instrumentation Ltd, 2010).

Figure 2. Hobo data logger used to measure indoor air temperature.

NatCen interviewers asked the occupants to place the sensors in the living room and main bedroom. Guidance was provided, which stated that they should be placed away from heat sources and not in direct sunlight. 108 households did not want to take the sensors (Fig. 1). At the end of the monitoring period households were asked to return the sensors in pre-paid envelopes, these arrived back between late March 2010 and August 2011! In all 621 sensors were returned from 319 households, 150 households did not return them[5] (Fig. 2), which represents a data loss rate of 47%.

Weather measurements

Long-term temperature data was available from Leicester City Council's weather station but more detailed and complete hourly weather data for the monitoring period was obtained from De Montfort University (Fig. 3). The location of both sites is in the centre of the map (Fig. 1).

The temperatures from 1st July to 31st August are the focus of this study. During this period, the external temperature varied from 7.9°C to a peak of 29.7°C and the total solar radiation values reached 968W/m^2 on 15th July (Fig. 3). The start of the monitoring period was hot. Beginning on 28th June, the average daily temperature exceeded 19°C for five successive

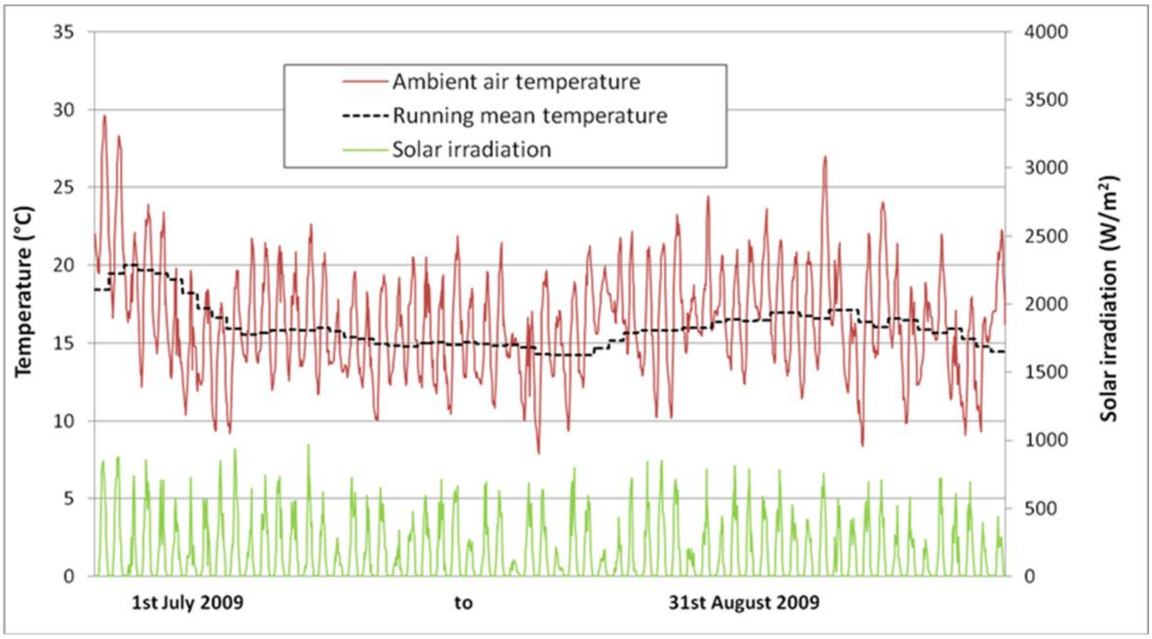

Figure 3. External temperature, solar irradiance and running mean of daily average temperature

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[5] Or were not offered them by the interviewer.

days reaching 24.1^{o}C on July 1st but falling back to 18.8^{o}C on July 3rd. Thereafter, it was below 19^{o}C for all but one day during the rest of the monitoring period. The highest daily average temperature recorded in Leicester in the 10 years from 2000 and 2009[6] was 25.8^{o}C on 25th July 2006 and it has only exceeded 24.1^{o}C on 11days, i.e. only 3 days in 1000 are warmer than July 1st 2009. The recorded running mean of the external temperature, T_{rm}, as defined in BSEN15251, 2008 (see below) reached 20^{o}C on July 3rd. This is similar to the value recorded during the 2003 heat wave (20.5^{o}C) but below the 97th centile value[7] of mean daily temperature for 2000 to 2009 of 20.5^{o}C, and well below Leicester's highest ten-year T_{rm} value of 22.4^{o}C on 26th July 2006, when it was over 20^{o}C for 13 successive days.

By way of comparison, Wright et al. (2005) noted that during the 2003 heat wave, average daily temperatures exceeded 19^{o}C for 9 successive days in Manchester and in London 20^{o}C was exceeded for more than 12 days. In Manchester, the maximum daily mean temperature was 25.4^{o}C with an absolute peak of 32.1^{o}C; corresponding values for London were 29.3^{o}C[8] and 37.4^{o}C. Thus, whilst hot for Leicester, the temperatures in early July were modest compared to those recorded in other larger cities during an extreme heat wave.

Considering the whole period, the average temperatures were 16.2^{o}C and 16.6^{o}C in July and August respectively compared to the Leicester 10 year averages of 17.2^{o}C and 17.1^{o}C respectively. Thus, overall, the monitored period was cooler than normal for the time of year. The running mean temperatures support this perception; throughout the two month period, the T_{rm} value exceeded 16^{o}C for 39% of the time and 18^{o}C for 13% of the time, compared to the Leicester ten year average figures for July and August of 51% and 23% respectively.

Given the weather conditions, the measured indoor temperatures will give information about temperatures during a hot spell of weather but not about conditions during prolonged hot weather, i.e. a heat wave. The hot spell means that the data covers a wide range of external temperatures over which to assess the measured indoor thermal comfort.

Thermal comfort evaluation

Alternative methods for assessing the risk of overheating and thermal comfort in the homes were reviewed. The Chartered Institution of Building Services Engineers Guide A (CIBSE, 2006), which is the standard most often used in the UK to guide the thermal design and performance evaluation of buildings, gives target temperatures for living rooms and bedrooms of 23-25^{o}C. The Guide states that "*during warm weather 25^{o}C is an acceptable temperature*" for the living areas of dwellings and it offers a thermal comfort criterion against which to evaluate thermal models' predictions: a limit of "*1% annual occupied hours over operative temperature of 28^{o}C*". Thresholds of 25^{o}C and 28^{o}C underpin a number of international criteria for evaluating annual overheating risk (e.g. Eppel & Lomas, 1992; Cohen et al., 1993) with 5% of hours over 25^{o}C or 1% of hours over 28^{o}C being given as allowable annual exceedences. They have been used to assess overheating risk in CIBSE documents (e.g. CIBSE, 2005). In this paper, 'static' criteria of 5%/25^{o}C and 1%/28^{o}C, as measured during the monitoring period, are used, respectively, as indicators of mild and severe summertime overheating risk in living rooms.

Concerning bedrooms, the CIBSE guide notes that "*thermal comfort and quality of sleep begin to decrease if bedroom temperatures rise much above 24^{o}C*" and that "*bedroom temperatures at night should not exceed 26^{o}C unless ceiling fans are available*", the

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[6] As recorded by Leicester City Council in the middle of Leicester.

[7] This is the threshold above which Hajat et al. (2002) calculate death rate increases.

[8] In Leicester, the temperatures in August 2003 reached 37.0^{o}C (on August 9th) with a maximum daily mean of 24.2^{o}C and a maximum T_{rm} value of 20.5^{o}C.

overheating criterion to be used in association with predicted temperatures is that there should be no more than "*1% annual occupied hours over an operative temperature of 26°C*". In this paper, 5% of hours over 24°C and 1% over 26°C, as recoded during the monitoring period are used as markers of mild and severe summertime overheating risk in bedrooms.

Others have used the same criteria to evaluate indoor temperatures, for example, Wright et al., (2005) used hours over 25°C and 28°C in their study of temperatures during the 2003 heat wave. In their modelling study, Peacock et al. (2010) use 28°C as a threshold for living rooms and 23.9°C at 23:00 for bedrooms, and in their modelling work, Hacker et al. (2008) deemed that a building was overheated if in any year more than 1% of occupied hours exceeded 28°C for living rooms and 26°C for bedrooms. Both Hacker et al. and Wright et al. assumed occupancy of an adult bedroom to be from 23:00 to 07:00. To maintain consistency with this previous work, the same period is assumed herein.

Whilst 'static' criteria are helpful for rapidly comparing temperatures in different homes, in practice, individuals will adapt to changing temperatures: by wearing more or less clothing, taking hot or cold drinks, being more or less active, or by adapting their surroundings, for example, increasing ventilation by opening and closing windows and trickle vents and creating shading by closing curtains and blinds. Thus, adaptive thermal comfort criteria may be much more appropriate for assessing the internal conditions in homes.

In summer, UK homes are likely to be free-running i.e. not heated or mechanically cooled. The internal temperature therefore drifts with the change of external temperature and the expectations of people differ similarly; they wear less clothing in summer than in winter, for example. Thus, in summertime, people are likely to be better adapted to conditions in free-running buildings and find them more comfortable than those in artificially cooled spaces[9].

Contemporary adaptive thermal comfort standards provide comfort envelopes that drift with the external temperature. The most relevant standard for UK dwellings is British Standard and European Norm BSEN15251 (British Standards Institute, 2008), which "*specifies methods for long term evaluation of the indoor environment obtained as a result of calculations or measurements*" and is applicable to "*single family houses*". The standard

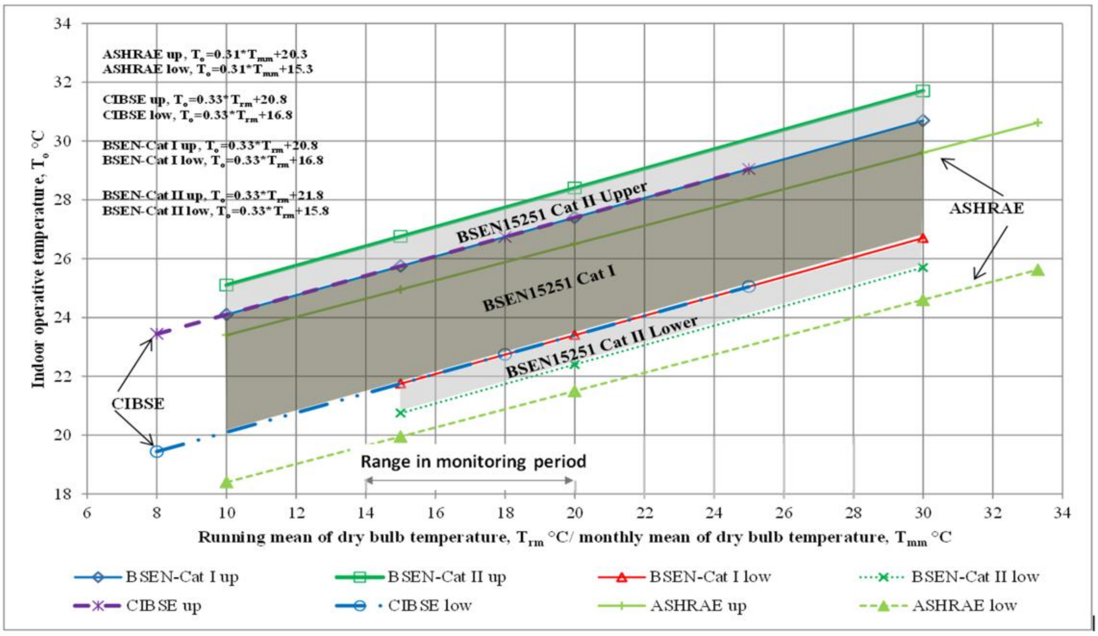

Figure 4. Comparison of adaptive thermal comfort standards (after Lomas and Giridharan, 2012)

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[9] The chill of entering air-conditioned spaces on a summer day will be familiar to many.

provides comfort envelopes with thresholds that increase at a rate of 0.33K per K as the running mean of the external temperature (T_{rm}) increases within the range $10<T_{rm}<30^oC$[10].

The Category (Cat. I) envelopes define a 4K range temperatures for each value of T_{rm}; Cat. II a wider range 6K range and Cat. III, a wider envelope still 8K (Fig. 4). These are defined as Cat. I "High level of expectation[11]" Cat. II "Normal level of expectation", and Cat. III "An acceptable, moderate level of expectation and may be used for existing buildings", with Cat. IV "Values outside the criteria", which "should only be accepted for a limited part of the year". Applying standard comfort theory calculations, Cat. I, II, III correspond respectively to 6%, 10%, and 15% of predicted dissatisfaction in normal health people, see PPD in ISO 7730 (International Standards Organisation, 2005)[12].

The CIBSE Guide A gives adaptive thermal comfort envelopes that are identical to the BSEN15251 Cat. I envelopes, but applicable down to a T_{rm} value of 8^oC (Fig. 4). The US standard, ASHRAE 55 (ANSI/ASHRAE, 2010) provides adaptive envelopes that are based on the monthly mean external temperature, T_{mm}, which increases at a rate of 0.31K per K over the range $10<T_{mm}<33.5^oC$ (Fig. 4). Wright et al. (2005) used an earlier form of this envelope (De Dear & Brager, 2001) to evaluate indoor temperatures in the 2003 heat wave.

The BSEN15251 categories provide a credible way of evaluating the measured internal temperatures in the monitored dwellings. The standard does not place strict limits on the allowable exceedences of the category boundaries, although five methods of quantifying exceedences are offered. Of these, the simplest is the percentage of hours outside a category boundary. Here, 5% of hours above or below a category boundary is used as a marker for warm discomfort or cold discomfort.

Measured data preparation

The data from the returned sensors was downloaded and attached to the corresponding household data, with the exception of 6 sensors which would not download and 7 for which the interviewers had recorded the incorrect serial numbers making it impossible to attach the sensor data to a particular property. Thus data was obtained from 312 households of which 284 had both living room and bedroom data, 18 for living room only and 10 for bedroom only: 596 data traces in all.

The hourly data was plotted for the period 1st July to 31st August 2009 and inspected by eye. This immediately revealed a number of anomalies, in particular sensors that had not been placed correctly or were not working. This data were excluded from the data set but only when there were clear grounds for exclusion; when there was uncertainty, the data remained in the dataset. This process revealed some anomalies for which explanations are is proffered: cases where both sensors were recording identical temperatures (consistent with a situation where sensors had been left together - 9 houses); step changes in the temperature profile (consistent with a sensor being moved - 10 sensors); sensors recording very close to external temperature (consistent with them having been placed outside or in a porch - 3 sensors); extreme responses that correlated with solar radiation (consistent with the sensor being left in sunlight - 12 sensors); and profiles that were extremely unresponsive to ambient signals (consistent with sensors being placed in a container, cupboard or drawer etc - 5 sensors).

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[10] $T_{rm} = (1-\alpha).\{T_{ed-1} + \alpha.T_{ed-2} + \alpha^2.T_{ed-3}.....\}$; where T_{ed-1} is the daily mean external temperature the previous day, T_{ed-2} the daily mean external temperature two days ago, etc., and α has a recommended value of 0.8.

[11] This is the recommended category for spaces "occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons".

[12] The standard also offers temperatures for the winter heating season of 21, 20 and 18^oC for Cat. I, Cat. II and Cat. III respectively.

In addition to these exclusions, data from 13 sensors indicated there were problems with the internal clock. Finally, some temperatures' traces suggested periods of abnormally low temperatures, perhaps because the houses were unoccupied, a summer holiday perhaps (4 houses). Excluding the 35 households where both the living and bed rooms had measurement errors (Fig. 1), this left a data set of 282 homes, with useable data from either the living room or the bedroom or both.

The distribution of house types and household size in this sample reflects that of the city as a whole. However, the percentage of those owning their property either outright or with a mortgage (68% in the sample of 282 homes) seems to be much greater than in the city as a whole (58%) with the percentages renting being less, 30% in the sample and 40% in the city as a whole. However, the data for the city is from the 2001 census (ONS, 2010) and new owner-occupied homes have been built and some previously rented will have been bought, thus our sample might actually be representative of Leicester today.

From the plotted data, 52 of the homes seemed to show some evidence of being heated in one or other of the rooms at some time during the monitoring period. However, it was difficult to determine unambiguously whether the changes in sensor temperature were due to space heating or to some other effect; for example, exposure to radiant heat sources (e.g. from sunlight or tungsten halogen lights) or a thermal plume from a convective source (e.g. near a radiator, or over a warm electrical device). Where there was uncertainty, the temperature records were ignored. This left 38 homes (i.e. 13% of the sample of 282) in which one or other of the rooms evidenced space heating (Table 1).

The remaining 230 homes (i.e. 82%) had no obvious heating in either of the monitored rooms at any time in the monitoring period,

		Leics UA	Free floating		Heated	
			No.	%	No.	%
Data available	Both spaces		186	81%	3	8%
	Living rm. only		26	11%	28	74%
	Bedroom only		18	8%	7	18%
	Total homes		230		38	
House type	Detached	10%	21	9%	3	8%
	Semi detached	37%	96	42%	24	65%
	Mid terrace	35%	62	27%	6	16%
	End terrace		23	10%	1	3%
	Flat	17%	28	12%	3	8%
House age	Pre 1900		19	8%	2	5%
	1900-1919		27	12%	4	11%
	1920-1944		72	31%	13	35%
	1945-1964		41	18%	12	32%
	1965-1980		36	16%	2	5%
	Post 1980		35	15%	4	11%
Wall type	Solid		105	45%	17	46%
	Cavity		57	25%	5	14%
	Filled cavity		68	30%	15	41%
Tenure	Own outright	24%	89	39%	15	41%
	Own mortgage	34%	71	31%	7	19%
	Rent	40%	66	28%	13	35%
	Other	2%	4	2%	2	5%
Oldest occupant	20 years		15	7%	0	0%
	30 years		34	15%	4	11%
	40 years		56	24%	10	27%
	50 years		39	17%	4	11%
	60 years		46	20%	6	16%
	70+ years		40	17%	13	35%
Household size	1	32%	63	28%	10	27%
	2	29%	79	34%	15	40%
	3	15%	33	14%	4	11%
	4	14%	35	15%	7	18%
	5	7%	14	6%	0	0%
	6	2%	5	2%	1	3%
	7	1%	1	1%	0	0%
Loft insulation	Don't know		16	7%	0	0%
	n/a		49	21%	8	22%
	none		0	0%	0	0%
	0-50 mm		31	14%	3	8%
	50-100 mm		51	22%	11	30%
	100-200 mm		40	17%	8	21%
	200+ mm		43	19%	7	19%

Table 1. The samples of free-floating and heated homes

i.e. they were free-running.

The data cleaning process resulted in further loss of data bringing the overall attrition rate, due to non-returns and data rejection, to 49%. Clearly, the sensor placement protocol is an important factor in temperature surveys and it is recommended that, to avoid misplacement, a trained individual should locate them. The cost of doing this could however be high and insistence on this approach might compromise data collection, if occupants are reluctant to have others enter some rooms. Further, there no guarantee the sensors would remain undisturbed throughout the measurement period.

Data Analysis: heated homes

The heated spaces displayed large and frequent temperature changes, often up to the same peak value (the set-point perhaps) and sometimes following a regular pattern (evidence of a timer in use). In homes where both the living room and bedroom were heated, the temperature changes were in synchrony suggesting a central heating system was switched on. As an illustration, Figure 5 shows a regular pattern of night time heating in the bedroom of a rented flat occupied by a single elderly person; there is also evidence of heating in the living room after the internal temperature fell below 23°C in early August.

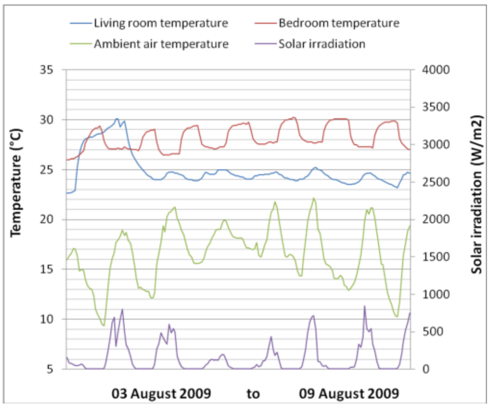

Figure 5: Bedroom heated each evening, in a house occupied by a single elderly person.

In the 31 heated living rooms, the average temperature between 08:00 and 22:00 was 23.5°C although the hottest room had a mean of 28.2°C and a maximum of 33.7°C! Considering the static CIBSE overheating criteria, the temperature in this room exceeded 25°C for 99% of the time and 28°C for 67% of the time. Considering all the heated living rooms, 26 of the 31 rooms had more than 5% of hours over 25°C and 17 exceeded 28°C for more than 1% of the time.

In the 10 homes with heated bedrooms, the overall mean temperature between 23:00 and 07:00 was 23.4°C and the hottest bedroom reached 37.4°C! Nine were heated such that there were more than 5% of hours over 24°C and more than 1% of hours over 26°C. Clearly, high night time temperatures are preferred by some occupants.

Within the sample of heated homes, the proportion of each house age, wall construction and household size was not significantly different from the proportions in the whole sample of 282 homes. There were however more semi-detached homes ($p<0.05$). More importantly, in 13 of the heated homes (i.e. 34% of them) the occupants were over 70 years of age (with 7 of them living alone). This is significantly more over 70's ($p<0.02$) than the 19% that would be expected if equally distributed across heated and unheated homes.

The greater tendency for elderly people to heat their homes in summer, could be, in combination with hot weather, quite literally, a lethal combination because thermal sensation deteriorates with age, blunting adaptive behaviour, rendering older people particularly susceptible to elevated temperatures. This observation suggests that heat wave public awareness campaigns should include the obvious and simple advice to turn off heating systems and any other source of heat; this could be incorporated in the NHS heat wave plan for example (NHS, 2011).

Data analysis: unheated homes

Within the sample of 230 free-running homes, temperature data was available for both rooms in 186 homes, for the living room only in 26 and the bedroom only in 18, thus data was analysed for a total of 212 living rooms and 204 bedrooms.

In general, the free-running rooms exhibit drifts in temperature in response to the changing external temperature but with attenuation and some time lag (Fig. 6). Overlaid on this general behaviour were more rapid temperature rises due to solar gains and internal heat gains from appliances etc; the latter being most obvious in living rooms in the evenings.

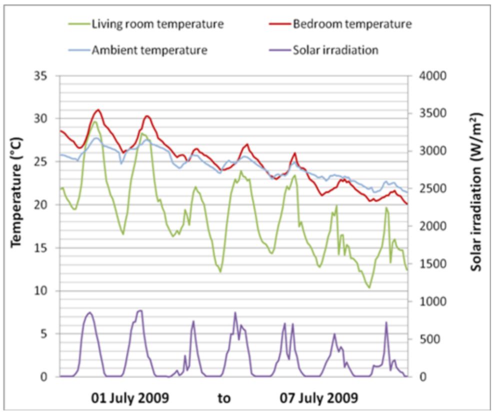

Figure 6: Example of temperatures in an unheated home.

Whereas in homes with heated spaces, the temperatures in the two rooms varied in different ways (e.g. Fig. 5), in the free-running houses, they tended to be more synchronised (Fig. 6). Across all 212 free-running living rooms, the average mean temperature recorded between 08:00 and 22:00 across the two-month period was 22.2°C; the range in the means was from 25.2°C to 19.0°C. The highest single hourly temperature recorded in a living room was 32.6°C and the lowest 14.8°C. The mean temperatures recorded in the 204 bedrooms between 23:00 and 07:00 in the two month period varied from 25.1°C to 18.8°C with and average mean of 22.4°C. The highest single hourly temperature recorded in any bedroom was 35.0°C and the lowest 14.1°C. Thus, despite the milder weather conditions, the hottest free-running Leicester homes had peak temperatures comparable to those recorded in the 2003 heat wave in Manchester; 30.0°C in a living room and 36.0°C in a bedroom.

In the 186 homes with measurements in both rooms, the greatest differences between the mean living room temperature and the mean bedroom temperature were +3.7°C (living room warmer) and -3.5°C (bedroom warmer). There were 76 homes where, on average, the living room was warmer than the bedroom and 111 where on average the bedroom was warmer (Fig. 7). For many homes there was no clear tendency towards either a warmer bedroom or

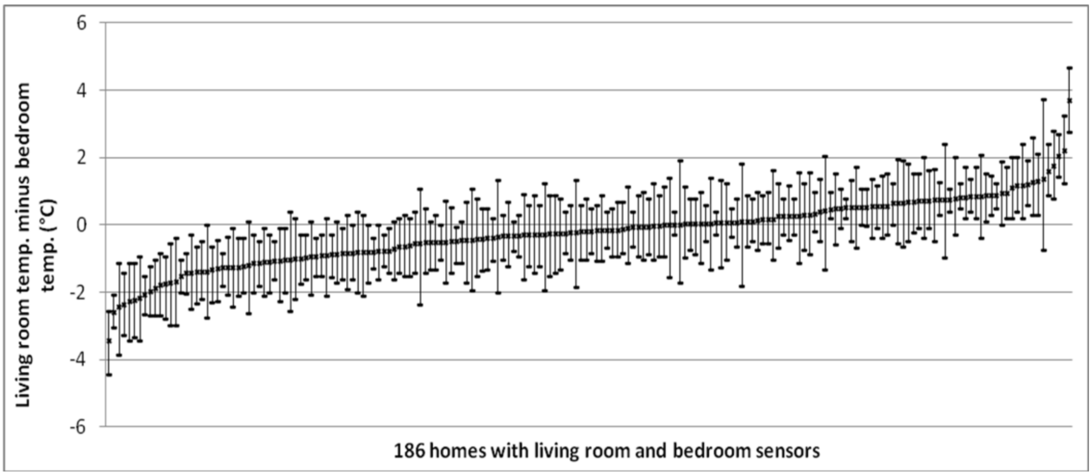

Figure 7: Difference between the mean living room and bedroom temperature and the 10th and 90th percentile differences.

warmer living room. However, in 48 homes the living room was warmer for 90% of the time or more. Significantly more of these were built between 1945 and 1965 than would be expected if evenly distributed ($p<0.02$). In 26 homes, the bedroom was warmer for 90% of hours or more. These included significantly more households with just one or two members (as typifies the elderly) and significantly more modern, post-1980s homes ($p<0.04$).

Analysis of free-running rooms: CIBSE static criteria

The percentage of hours over 25°C and 28°C are shown for the living rooms in Figure 8 and over 24°C and 26°C for the bedrooms in Figure 9. It is evident that many spaces exceed the indicators of mild overheating risk, 25°C and 24°C, for many hours during the monitoring period; 10% of the living rooms exceeded 25°C more than 25% of the time, and 10% of bedroom exceeded 24°C more than 55% of the time.

Of the 212 living rooms, 122 (i.e. 58%) exceed the 5%/25°C indicator of mild overheating when considering the whole day (08:00 – 22:00) (Fig. 8) and 133 (i.e. 63%) when considering the evening only (18:00 – 22:00)[13]; i.e. when more living rooms are more likely to be occupied with additional internal heat gains. Considering the 28°C/1% criterion as a marker of extreme overheating, 58 of the homes (i.e. 27%) exceeded this when considering the whole day and 64 (i.e. 31%) when considering just evening hours.

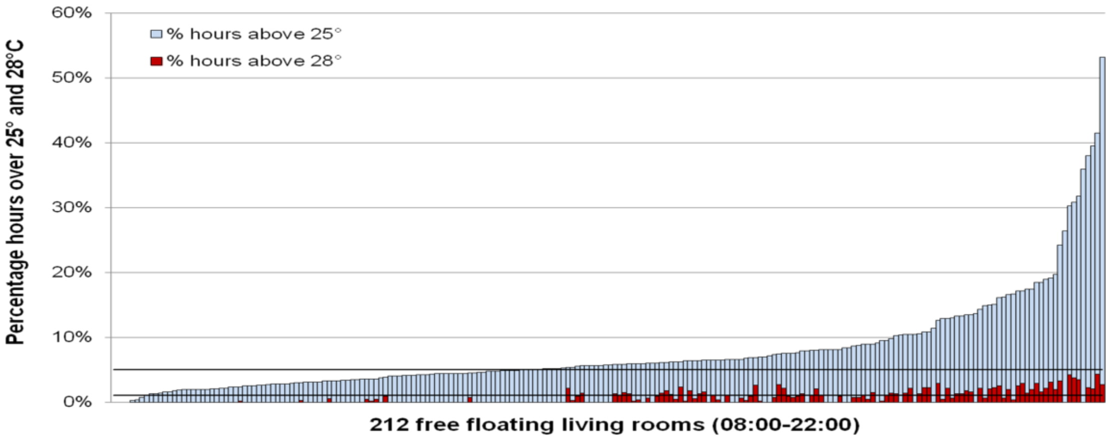

Figure 8: Measure temperatures and CIBSE overheating criteria, free-floating living rooms

There were significantly more flats with over 1% of hours above 28°C than other house types, i.e. 13 (46%) when considering the whole day ($p<0.03$) and 13 (42%) when considering the evenings only ($p<0.01$). This finding aligns with observations of previous researchers and the national heat wave plan, that top floor flats are at particular risk. The living rooms of solid wall properties were found to be significantly less likely to be warm, as judged by either criterion and by both whole day and evening only analyses ($p<0.04$) suggesting, as is perhaps to be expected, that exposed thermal mass confers protection against elevated temperatures.

Considering the 204 bedrooms, during the evening (23:00 – 07:00), 92% exceeded the 24°C/5% criterion and 88% the 26°C/1% criterion (Fig. 9). Bedrooms in flats were, however, no more likely to be hot than the bedrooms in other house types, although homes built in the period 1966-80 were significantly more likely to exceed the 1%/26°C criterion ($p<0.03$).

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[13] Not shown herein.

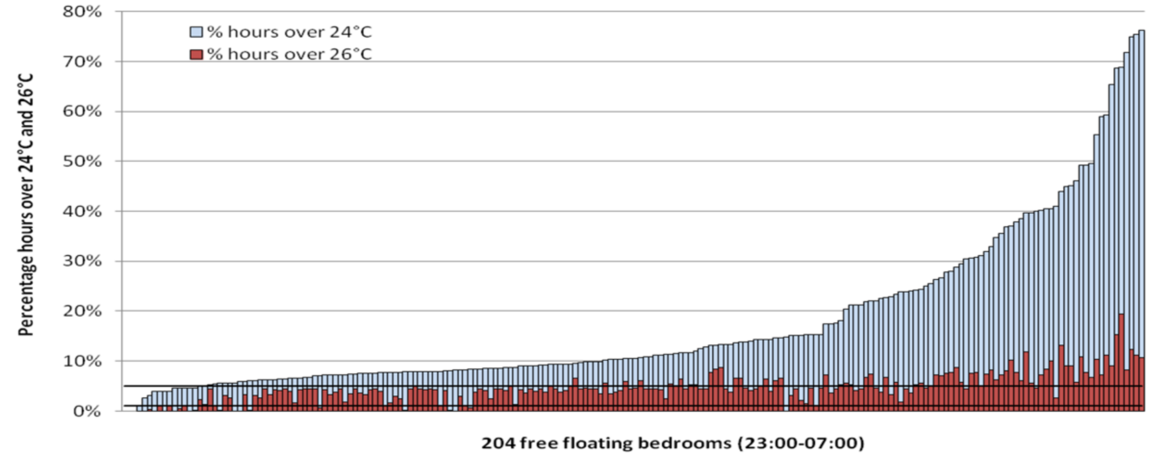

Figure 9: Measure temperatures and overheating risk indicators, free-floating bedrooms

Analysis of free-running rooms: adaptive thermal comfort criteria

The impression gathered from the application of the static overheating criteria is that there was overheating in many Leicester city homes despite the overall cool summer conditions experienced. Analysis using the adaptive thermal comfort standard paints a rather different picture.

Plotting the measured hourly temperatures against the running mean of the daily average external temperature (T_{rm}) revealed the expected trend towards warmer indoor temperatures as T_{rm} increased (Fig. 10 and 11). The ranges in internal temperature for a given T_{rm} value could be quite different from one home to the next (Fig. 10 cf. Fig. 11).

During the hot spell (T_{rm}>18°C), some rooms exceeded the Cat. III threshold (Fig. 10). Other homes were notably cooler with less variation in the daily temperatures; some were frequently below the Cat. II, and even the Cat. III threshold in cooler weather periods (Fig. 11).

An overriding tendency for cool, rather than warm, discomfort during the monitoring period is clearly illustrated when the percentage of time that temperatures are within

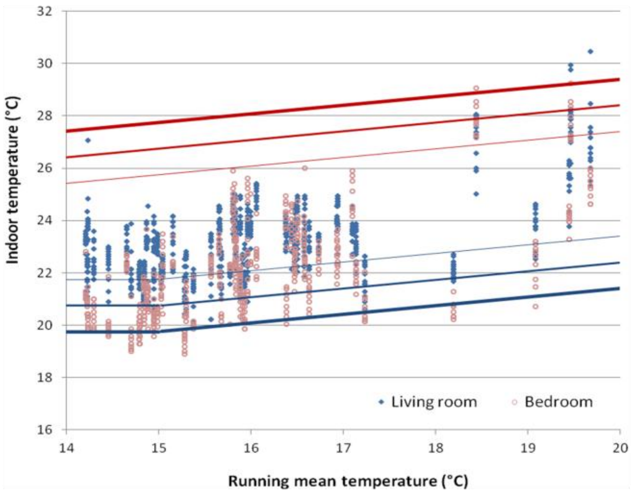

Figure 10 Temperatures measured in a warmer home and BSEN15751 thresholds

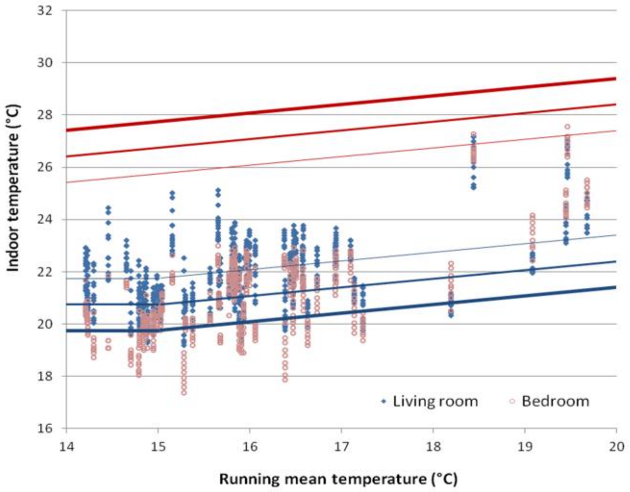

Figure 11 Temperatures measured in a cooler home and BSEN15751 thresholds

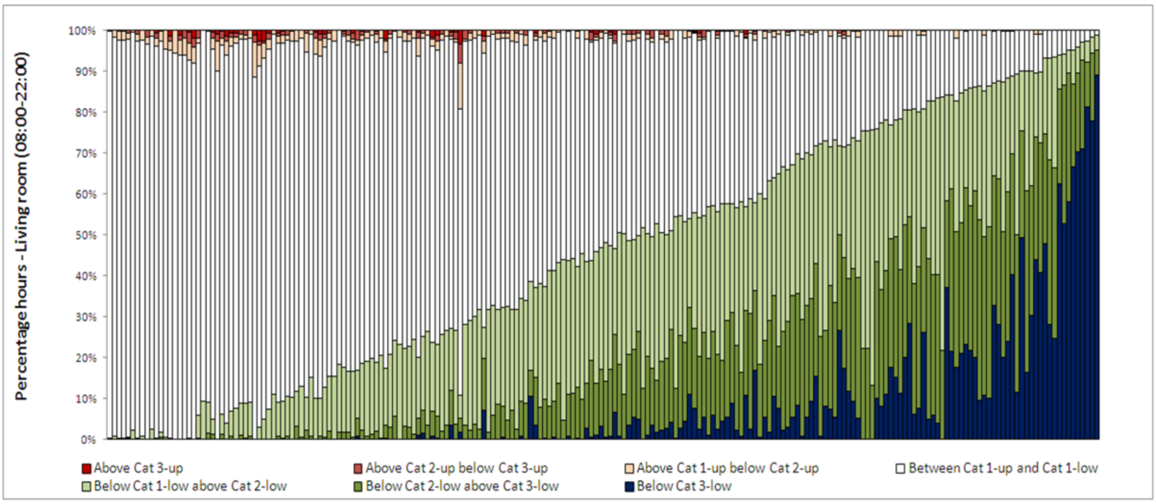

Figure 12: Occurrence of living room temperatures in each BSEN15251 thermal comfort category

each comfort category in all the homes is plotted (Fig. 12 and 13[14]). These results can be assessed using the simple BSEN15251 criterion that there should be no more than 5% of occupied hours outside a desired comfort threshold.

Considering firstly Cat. II, 'normal level of expectation', there was just 1 living room and 5 bedrooms (2%) with more than 5% of hours above the upper threshold, but 136 living rooms (64%) and 144 bedrooms (71%) with more than 5% of hours below the Cat. II lower thresholds. In fact, there were 73 living rooms (34%) and 99 bedrooms (49%) below the Cat, III lower threshold '…. moderate level of expectation, may be used for existing buildings' more than 5% of the time. The greater occurrence of cool bedrooms is to be expected, of course, as the temperatures plotted are for the night time.

There are a number of reasons that the temperatures are so low, most obviously because most UK homes tend to be unheated during the summer time (e.g. 230 of the 282 in this study, 82%). Even when the temperatures are low, heating systems tend not to be switched on, and instead additional clothing tends to be worn. Some of the homes may also be lightly occupied or un-occupied for more time in the summer.

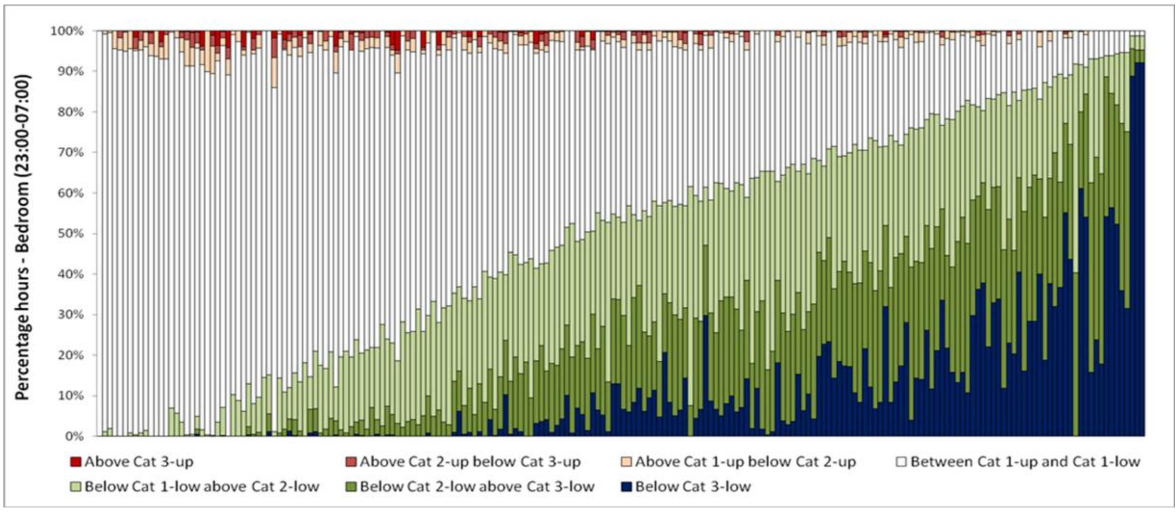

Figure 13: Occurrence of bedroom temperatures in each BSEN15251 thermal comfort category

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[14] Data are ordered from left to right by the percentage of time within the Cat I boundaries.

The evidence from this study is that summertime temperatures in unheated UK homes may well not conform to the expectations described by the BSEN15251 adaptive comfort model. Homes, unlike places of work, which have provided much of the data on which the model was developed, tend to have much lower internal heat gains and lower occupancy densities. Internal temperatures are also dominated by heat flux through the building fabric, whereas non-domestic buildings usually have a much smaller volume to external area ratio. In the UK, some homes are also poorly insulated and rather leaky thus they can cool rapidly when external temperatures drop. However, this is just one study in one locality and further work to shed more light on these matters is encouraged.

Conclusions and further work

1. The “drop and collect” method for measuring internal house temperatures resulted in useable data from just 49% of the targeted spaces. This was because either the households did not return the sensors or because the data was corrupted or unreliable. This was a well-conducted study, using a professional survey company. Such a high loss of data is expensive.

   Of the usable data, it was sometimes unclear which rooms were being purposely heated and which were warmed by other sources of internal gain, lights, TVs etc. This was exacerbated because households were asked to place the temperature sensors and some could have been located rather close to such sources of internal heat gain.

   One clear recommendation of this study is that reliable space temperature monitoring is only likely to be possible if temperature sensors are located by trained members of the study team.

2. The monitoring period included a hot spell that lasted just 5 days but the two-month period was, overall, cooler than normal for Leicester city. The hottest free-running homes had peak temperatures in the living room and bedroom comparable to those recorded in Manchester in the 2003 heat wave, despite external conditions being less severe.

3. Those household members aged over 70 were significantly more likely to heat part of their home in summer than those in other age groups, some to high temperatures. This is particularly worrying as this will exacerbate the tendency of homes to overheat in warm weather and it is the aged that suffer most during such periods. It is suggested that the National Health Service heat wave plan includes advice that heating systems and other sources of heat should be turned off during warm weather.

4. Of the 212 monitored free-running living rooms, c.60% exhibited mild overheating and c.30% extreme overheating risk as indicated by the 5%/25^{o}C and 1%/28^{o}C criteria applied over the two month monitoring period. Compared to other house types, there were significantly more flats with extreme overheating risk and significantly fewer solid wall properties exhibited mild or severe overheating risk. These results align with others’ observations that flats are at particular risk during hot weather and that exposed thermal mass confers protection against elevated external temperatures. As judged by the 26^{o}C/1% criterion applied during the night time (23:00 – 07:00), 88% of the 204 monitored free-running bedrooms were at risk of severe overheating.

5. Analysis using the adaptive thermal comfort standard painted a picture of rooms being generally rather cool. Just 1 living room and 5 bedrooms had more than 5% of hours with temperatures above the Cat. II thermal comfort envelope. In contrast, there were 64% of living rooms and 71% of bedrooms in which temperatures were below the lower Cat. II

threshold for more than 5% of the time; in 34% of living rooms and 49% of bedrooms with temperatures below the Cat. III envelope over 5% of the time.

6. The evidence from this study is that the occupants of UK homes do not operate them in cool weather to achieve the internal temperatures anticipated by the BSEN15251 thermal comfort standard. Occupants seem to tolerate low internal temperatures when external temperatures are low and heating systems remain switched off.
7. Analysis is ongoing to examine the relationship of internal temperature to external temperature. An understanding of this relationship will enable the construction of empirical models and an ability to predict internal temperatures in future weather conditions and heat waves.

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