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National survey of summertime temperatures and overheating risk in English homes

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ABSTRACT

This paper presents one of the first national scale studies of summertime temperatures in English dwellings. Living room and bedroom temperatures were recorded in 207 homes across the England during the cool summer of 2007. Data was also collected by face-to-face household interviews. Fourteen homes (7%) were observed to be heated for part or all of the analysis period (July to August). Based on the BSEN15251 adaptive thermal comfort model, the 193 free-running dwellings would, in general, to be considered as uncomfortably cool. Over 72% of living rooms and bedrooms had more than 5% of hours below the BSEN15251 Cat II lower threshold, with over 50% having more than 5% of hours below the Cat III threshold. Detached homes and those built before 1919 were significantly cooler ($p < 0.05$) than those of other type and age. Static criteria revealed that, despite the cool summer, 21% of the bedrooms had more than 5% of night time hours over 26 °C; which is a recommended upper limit for bedrooms. The bedrooms of modern homes, i.e. those built after 1990 or with cavity walls, were significantly warmer ($p < 0.05$). The bedrooms in homes built prior to 1919 were significantly cooler ($p < 0.05$). The living rooms of flats were significantly warmer than the living rooms in the other dwelling types ($p < 0.05$). The incidence of warm bedrooms in modern homes, even during a cool summer, is of concern, especially as there is a strong trend towards even better insulation standards in new homes and the energy-efficient retrofitting of existing homes.

1. Introduction

The UK climate has been warming, with the central England annual average temperature increasing by about 1 °C [1] over the last century. This trend is expected to continue resulting in an increase in the annual average temperatures across the UK of about 2–3.5 °C by 2080 [1]. As a part of 2008 Climate Change Act, the UK government committed to reduce the greenhouse gas emissions by at least 80% compared to 1990 levels by 2050 [2]. The domestic sector accounts for 32% of total UK final energy consumption in 2010 [3], with 61% of the sector's energy consumption being dedicated to space heating [3]. Winter temperatures and reducing heating energy consumption have therefore attracted considerable attention within UK academia and the government. This paper focuses though on the summertime temperatures in English homes.

The impacts of high summertime temperatures in UK dwellings were experienced during the last decade's hot weather events. The European heat wave of August 2003 resulted in over 2000 (16%) additional deaths in England and Wales, with the highest impact in London and on the elderly [4]. Hajat et al. [5], by investigating the relationship between heat and mortality in London for a 21 year period, concluded that a growth in heat related deaths begins at a relatively low average external temperature of about 19 °C. The duration of exposure to high temperatures was also found to be an important factor in determining increased mortality.

Even if existing dwellings are adapted to accommodate temperature change, there is a risk that domestic mechanical air conditioning will become much more common in warmer areas of the country. Peacock et al. [6] used dynamic thermal simulation to investigate internal temperatures and estimated that 18% of householders in the south of England would install air conditioning by 2030 if they responded to warm temperatures in the same way as US householders. This would equate to 550,000 homes equipped

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Abbreviations: ASHRAE, American Society of Heating, Refrigeration and Air-Conditioning; BADC, British Atmospheric Data Centre; CaRB, Carbon Reduction in Buildings; CI, confidence interval; CIBSE, Chartered Institution of Building Services Engineers; DTM, dynamic thermal modelling; GOR, Government Office Region; NatCen, National Centre for Social Research.

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with air conditioning in London alone. Domestic air conditioning would further compound the difficulties associated with meeting the national carbon reduction targets.

Numerous studies have used dynamic thermal modelling (DTM) to predicting the possibility of overheating for different UK house types, constructions, occupant behaviours, and climate change scenarios, e.g. Refs. [6–9]. However, being based on modelling, such studies cannot capture the true behaviours of occupants and their interaction with heating and ventilating systems. Further models' limitations in predictive ability are usually ignored, and these limitations are significant. For example, in work by Lomas [10] predictions of peak temperature were found to have a simple resolution[3] of 3 °C for one particular UK house. This means that if one DTM predicts a particular peak temperature of, say, 26 °C, a different DTM might predict a value anywhere between 23 and 29 °C. By ignoring this inter-model variability, modelling studies tend to overstate the reliability of the results obtained.

By actually measuring the internal temperatures in dwellings, occupants' behaviour is fully captured and the limitations of modelling are avoided. Such studies are though, expensive and time consuming and so are rather rare. The data captured in the recent multi-university Carbon Reduction in Buildings (CaRB) project [11] offers a unique opportunity. In this paper, the internal temperatures measured during the summer of 2007 in 252 homes distributed across the England are examined using established static overheating criteria as well as BSEN15251 adaptive thermal comfort standard along with the associated house and household data that was captured through a face-to-face survey.

The aims of this paper are; to further our understanding of the summertime temperatures and thermal comfort in occupied English homes; to investigate the impacts of location, built type, age and wall type on these; and to compare static and adaptive thermal comfort criteria as measures of overheating risk. The paper expands on the work reported elsewhere for the UK city of Leicester [12] and is complementary to the analysis of the CaRB data presented in Kelly et al. [13]. Thus, to the authors' knowledge; one of the first large national scale studies of summertime temperatures and thermal comfort in English homes has been undertaken.

2. Materials and methods

2.1. Data collection

2.1.1. The CaRB dataset

A nationally representative sample of 1134 English dwellings was selected as part of the Carbon Reduction in Buildings (CaRB) research project [11] using stratified random sampling drawn from the Postcode Address File for England [14]. Postcode sectors were stratified by Government Office Region (GOR) and socio-economic class. After stratifying, 54 postcodes, and for each of those 21 addresses were randomly selected. Before approaching a household at their address, the National Centre for Social Research (NatCen) interviewers sent personalised letters about the study and a proposed interview date and time. Interviewers could also enclose a leaflet explaining the study, or they could use the leaflet at the address when asking to interview the householder. Interviewers, who were highly trained in maximising response rates when householders came to the door, would reschedule interview times to suit the convenience of householders and would also call back several times if householders were not at home. Altogether, 427 households agreed to participate in the study (a response rate of 37%). Interviews were conducted from 2007 to 2008 using a questionnaire devised by the CaRB project team that was intended to capture a wide range of information such as the households' energy consumption, heating practices, building characteristics and socio-demographics. Of the 427 households which were interviewed, 390 agreed to house at least one temperature sensor and useable data from 252 of these was used in this study. The HOBO pendant sensors (Fig. 1, Table 1) were to be placed in the main living room and main bedroom of each home either by the interviewer and the householder together, or by the householder on their own and returned at the end of the monitoring period. Written advice was provided to the DomNat surveyors, and a leaflet was provided for householders, advising on suitable sensor placement (between head and knee height, away from windows or doors and out of sunlight or any heat sources). The sensors recorded temperatures at 45 min intervals from 21 July 2007 to 10 March 2008 [15]. This recording interval was selected according to battery life and the internal memory capacity of the HOBO sensors in order to ensure their capability for the long monitoring period while still capturing the short term temperature fluctuations. The HOBO sensors were self-contained data loggers and the recorded data were downloaded from them only at the end of the study once the sensors had been collected from homes. The temperature database, along with the completed survey questionnaires, forms the backbone of the study reported here.

Fig. 1. HOBO pendant temperature loggers used for indoor temperature monitoring.

Following data cleaning, only 207 of the 252 households' sensors were found to have produced reliable data (see Section 2.2). These homes are located in 53 different local authorities, in the nine Government Office Regions of England (Fig. 2).

Compared to the English housing stock as a whole, as profiled by the national Census of 2001 [16], the sample studied contained

Table 1
Technical specifications of the HOBO sensors used for the temperature monitoring [15].

Parameter	Characteristics
Measurement range	−20° to 70 °C
Accuracy[a]	±0.53 °C
Response time	10 min
Time accuracy[b]	±1 min per month
Dimensions	58 × 33 × 23 mm

[a] For the temperature range of 0–50 °C.
[b] At 25 °C.

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[3] Simple resolution was defined as the value below which the absolute difference between the predictions of two programs (obtained by skilled users, for the same circumstances) may be expected to lie with a specified probability. In the absence of any other indication, the probability is 95%.

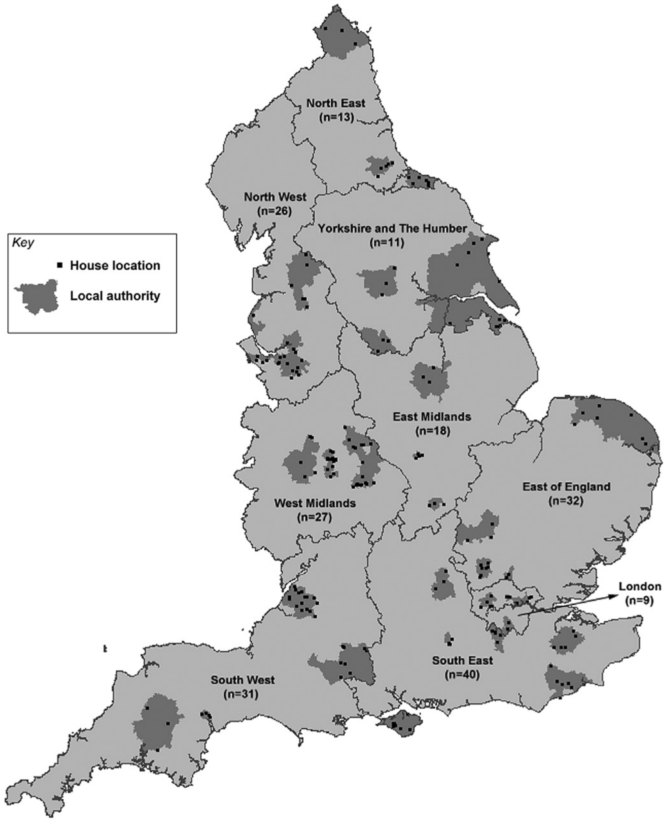

Fig. 2. Number of the dwellings in each Government Office Region and their approximate geographical distribution within their local authority boundaries.

proportionally fewer pre-1919 homes (13% cf. 21%, $p < 0.05$) and more homes built between 1945 and 1964 (27% cf. 20%, $p < 0.05$) (Fig. 3). There were proportionally more detached homes in the survey (34% cf. 23%, $p < 0.05$) but proportionally fewer purpose built flats (9% cf. 14%, $p < 0.05$). Also, and importantly for this study, there were proportionally far fewer homes in London (4% cf. 15%, $p < 0.05$) which, because of their location and effect of the urban heat island, are more likely to experience high summertime temperatures. There were though, proportionally more homes in the East of England (15% cf. 11%, $p < 0.05$) and the South West (15% cf. 10%, $p < 0.05$), which are warmer areas of England, and proportionally fewer in Yorkshire (5% cf. 10%, $p < 0.05$), which is a cooler region. Overall then, whilst the sample provides national coverage, there are features within it that make it unrepresentative of the national stock (Fig. 3).

2.1.2. *Weather data*

To understand the internal temperatures in each home in the context of the external temperature, weather data was sourced for local weather stations from the British Atmospheric Data Centre (BADC) [17] run by the UK Meteorological Office. The nearest weather station with hourly air temperature data was selected for each of the 207 dwellings according to their postcodes and the data downloaded from the MIDAS Land Surface Observation database [17]. Data from 30 weather stations was downloaded such that the nearest weather station to each home was less than 20 miles (32 km) away.

It was immediately evident that the warmest period for which monitored data was available was collected during a 41 day period from July 22nd to August 31st, thereafter the external temperature declined noticeably; the analysis reported here was therefore restricted to this 41 day period, called herein the ‘summer period’. The average hourly air temperature across all the weather stations

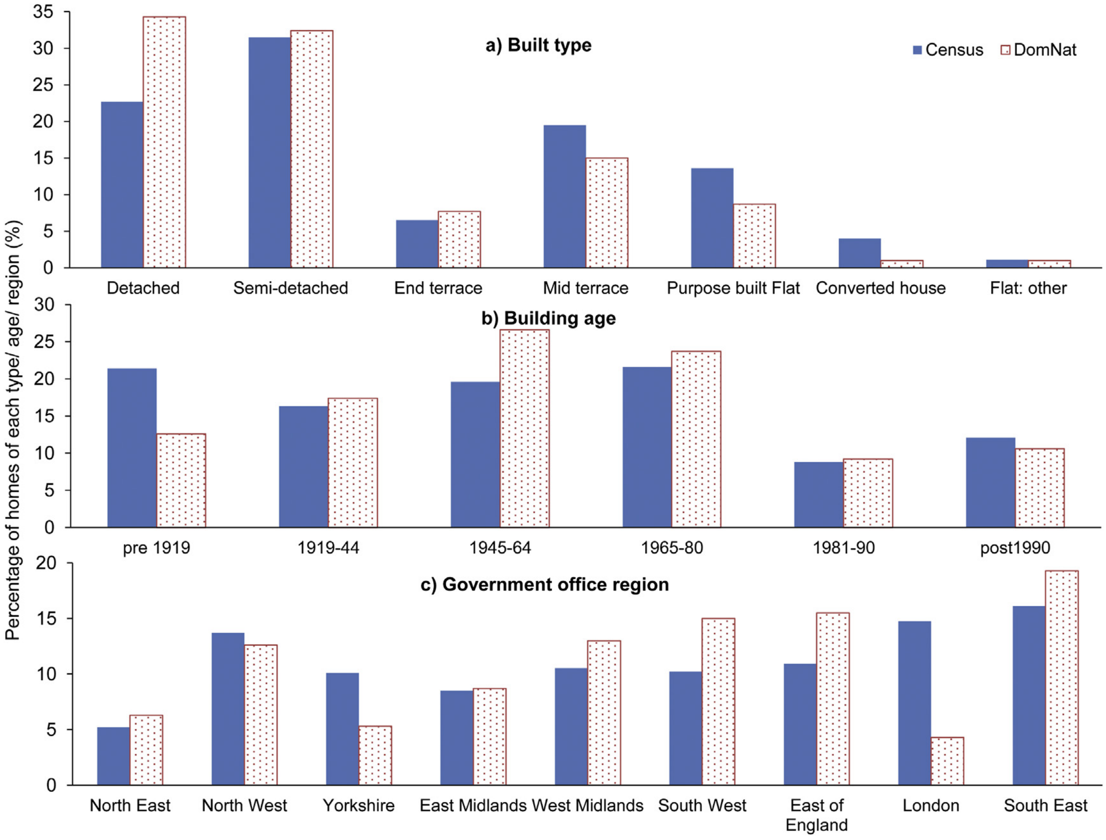

Fig. 3. Distribution of the dwellings within the sample of 207 by a) Built type, b) Building age band, c) Government Office Region, with comparison to the national 2001 Census data [16].

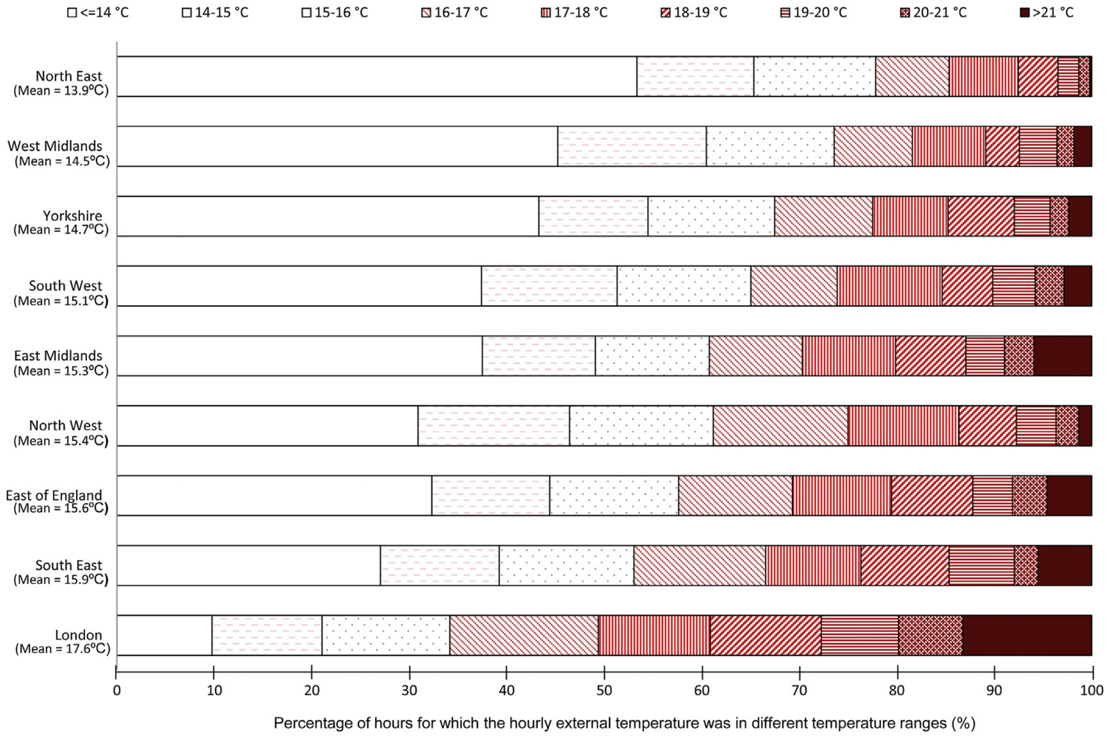

Fig. 4. Percentage of hours that the external air temperature was in different temperature ranges in each Government Office Region (regions ranked by their mean hourly external air temperature).

during this period was 15.3 °C and 15.4 °C for August only. This is substantially cooler than the August average of 16.4 °C for the preceding decade (1998–2007) [18] and in keeping with the Meteorological Office's assertion that the majority of England had its coldest August since 1993 [18]. The warmest region was London,[4] which, with a mean temperature for the monitoring period of 17.6 °C, was considerably warmer than the other regions. (The rest of the South East, was the next warmest at 15.6 °C). The hottest day was 5th August when the average daily temperatures ranged from 16.5 °C in Northumberland, North East to 24.0 °C in London. The maximum recorded temperature was 30.3 °C in London (August 5th). The maximum recorded at any of the weather stations during the rest of the analysis period was 27 °C (on August 4th also in London).

Analysis of the frequency of occurrence of temperatures in different temperatures bands (Fig. 4) confirms the extent to which London, with it substantial urban heat island, exceeds the temperature of the other regions. The London temperature exceeded 21 °C for 13.2% of the monitoring period, whereas in the next warmest regions, the South East, East Midlands and East of England, 21 °C was exceeded just 6% of the time or less. Not unexpectedly, the North East and North West had the lowest incidence of temperatures over 21 °C.

2.2. Preparation of measured data

Data preparation involved firstly matching the sensor data to the DomNat survey data for the 252 households that had returned temperature sensors. This process revealed nine sensors for which the serial numbers had been incorrectly recorded by the DomNat surveyor and so could not be attached to any property. In addition, it was found that in four homes only one sensor (living room or bedroom) had been returned. Since this is a small number compared to the whole sample, these four homes were omitted from the dataset so that analysis could proceed using both living room and bedroom temperatures for all dwellings.

To align the measured data with the hourly weather data, the measured internal temperatures, which had been recorded at 45 minutely intervals, were resampled assuming a linear temperature change over each 45 min interval. There were problems with internal clock of eight sensors so these homes eliminated from the dataset. The hourly external temperature along with hourly living room and bedroom temperatures were then plotted for the remaining dwellings.

The plotted data were inspected by eye to identify any errors and other anomalies. Where these were clearly evident, the dwelling was excluded from further analysis. If there was any uncertainty as to whether the data was real or anomalous it remained in the dataset. Anomalous data fell into one of five categories.

i. In five homes both sensors recorded identical temperatures, indicating that they had been left together in one place. It wasn't possible to tell whether this was a living room, bedroom or any other space.
ii. Eleven sensors showed extreme responses that were strongly correlated with solar radiation, suggesting that they had been placed in direct sunlight. They thus recorded much higher temperatures than those generally experienced by the household occupants.
iii. Three sensors showed a large step changes in the temperature profile, suggesting that they had been moved from their initial location. The temperatures might thus not reflect those of the living room or bedroom in which they were originally located.
iv. Six sensors recorded almost no change in temperature, suggesting that they had been put in an isolated place, like a cupboard or drawer.

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[4] External temperatures for a region were calculated as the average hourly external temperature across all the weather stations located in that particular region.

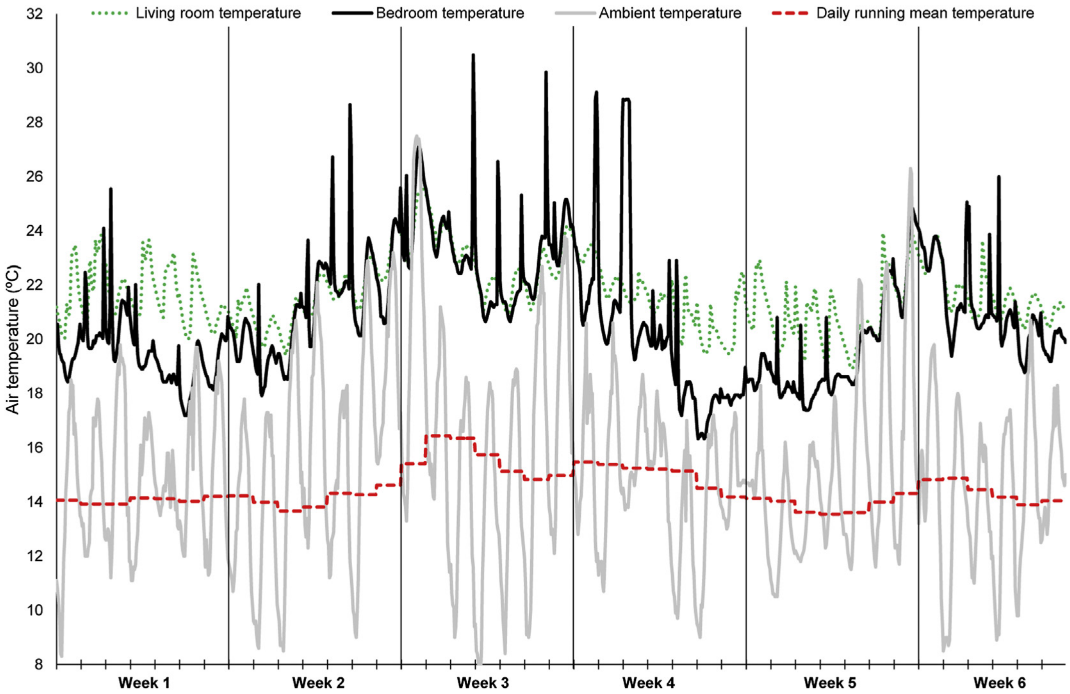

Fig. 5. Hourly air temperature variations in a home in Leicestershire (East Midlands region) with night time bedroom heating.

v. Finally, some sensors recorded temperatures very closely to the local external temperature. This could be due to the sensor being placed outside, for example a porch or other covered spaces.

After excluding all dwellings with these sensor anomalies, 207 dwellings with credible living room and bedroom temperature remained in the sample. Despite training the DomNat surveyors in sensor placement and the written advice to householders, there was an overall attrition rate of 18%; from 252 homes to 207 homes. The relatively high attrition rate could be explained as follows, "*while the instructions needed sufficient detail to ensure good placement, it was also important that the instructions were not so detailed as to discourage participants from accommodating the sensors, or encourage participants to ignore the instructions altogether*" [14]. This trade-off, between detail and simplicity of instructions, might have reduced the number of homes with reliable temperature data.

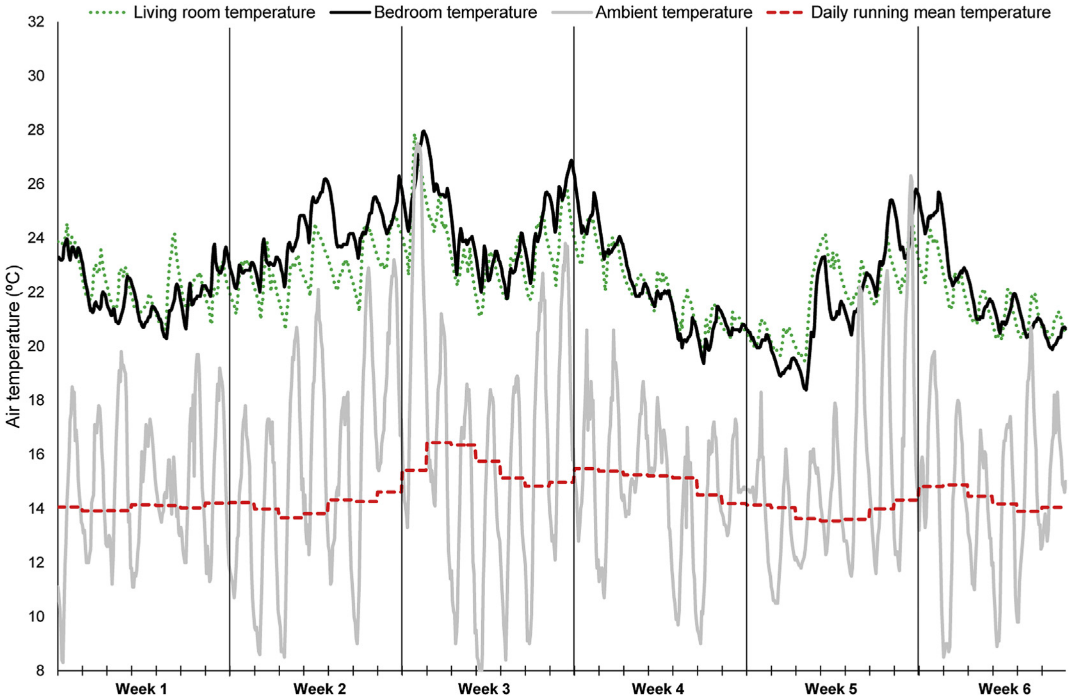

Fig. 6. Hourly air temperature variations in an unheated home in Leicestershire (East Midlands region).

Despite restricting the period of analysis, to the 41 days from 22nd July to 31st August, it was evident from the temperature traces that fourteen of the homes (7%) were heated either in living room or bedroom or both, at some point during the summer period. This was evident from the sharp increases in temperature that could not be explained by changes in the ambient conditions (e.g. Fig. 5). These sudden changes often followed a regular daily pattern. Because the primary aim of the study was to examine thermal comfort and overheating risk in free-running buildings,[5] these fourteen homes were also excluded from further analysis. In the remaining 193 free-running homes, the living room and bedroom temperatures tended to follow similar patterns (e.g. Fig. 6). The pattern heavily influenced by the trends in the ambient temperature although swing in internal temperature was, of course, invariably less than the swing in ambient temperature. Although the internal temperatures were generally higher than those outside, on isolated hot days, the interior could be slightly cooler (Figs. 5 and 6).

2.3. *Temperature assessment criteria*

2.3.1. *Static criteria for overheating risk*

The UK Chartered Institution of Building Services Engineers (CIBSE) Guide A [19] recommends operative summer temperatures of 23–25 °C for living rooms, and gives an overheating criterion, for use in evaluating the predictions of thermal models, that there should be no more than "*1% annual occupied hours over operative temperature of 28 °C*". Concerning bedrooms it is noted that at temperatures above 24 °C the quality of sleep may be compromised and that 26 °C should not be exceeded unless ceiling fans are available. This leads to the CIBSE overheating criterion, for use with models, that there should be no more than "*1% annual occupied hours over an operative temperature of 26 °C*". Many modelling studies have used 5% of occupied hours over 25 °C and 1% over 28 °C as indicators of overheating risk for living spaces and 5% of occupied hours over 24 °C and 1% over 26 °C for bedrooms, e.g. Refs. [4,20–22]. Monitoring studies have also adopted these thresholds [23] and, most importantly for this work, the city-scale study of summertime temperatures in homes by Lomas and Kane [12]. Keeping with the assumption about occupied hours adopted by earlier studies [22,23] the living room temperatures were examined for the period 08:00 to 22:00 and the bedroom temperatures from 23:00 to 07:00. However, the rooms may not necessarily have occupants during these times of the day for the whole monitoring period and it was not possible for the researchers to ensure that the participants were living inside their houses for the duration of the study. (I.e. do they work day/night shifts, did they go away on weekends or on holidays for particular periods?) Because the static criteria are applied here to the measurements made during a period of just 41 days, and not to a whole year, the thresholds of 24/26 °C and 25/28 °C, are merely being used to identify rooms that are uncomfortably warm. Thus, frequencies of occurrence in excess of 1% and 5% do not indicate overheating as defined by the CIBSE.

2.3.2. *Adaptive criteria for thermal comfort*

There are three major standards which offer adaptive thermal comfort criteria for the free-running buildings: ASHRAE standard 55 [24], CIBSE Guide A [19] and the British and European Standard BSEN15251 [25]. All operate using the concept that human beings adapt to the thermal conditions to which they have recently been exposed. Using this argument, supported by data from extensive field trials, the standards offer thermal comfort envelopes, with upper and lower thresholds of indoor operative temperature, that depend on the recent ambient temperature. These thresholds are applicable to near-sedentary individuals that are free to choose their clothing level. There are strong similarities between the thresholds proposed by the three standards (see e.g. Ref. [26]) although in the ASHRAE standard the indoor temperature thresholds increase with the mean monthly temperature whereas in the other two standards they increase with the exponentially weighted running mean of the daily mean ambient temperature (T_{rm})[6]; in both cases at a rate of 0.33 K per 1 K increase in T_{rm}. The variation of T_{rm} at one of the 30 weather stations that provided data for this study is illustrated in Figs. 5 and 6.

The BSEN15251 standard is particularly relevant, as it is applicable for assessing indoor temperatures derived by modelling and those obtained by measurement. The method offers three thresholds, which restrict the incidence of warm discomfort (upper threshold) or cold discomfort (lower threshold) in normal health sedentary people to: 6% of people (Cat I, thresholds are 4 K apart); 10% (Cat II, thresholds 6 K apart); or 15% (Cat III, thresholds 8 K apart). The Cat I thresholds represent a high level of thermal expectation and are identical to the CIBSE standard's thresholds. The Cat II thresholds are for a normal level of expectation and the Cat III thresholds represent an acceptable, moderate level of expectation and "may be used for existing buildings"; Cat IV values, which lie outside the Cat III thresholds, "should only be accepted for a limited part of the year". The standard offers five different methods of defining the level of thermal discomfort. The simplest is to calculate the percentage of occupied hours for which the indoor operative temperature lies outside the threshold(s) of interest. It is suggested that 5% of hours, in any day, week, month or year, is an acceptable limit.

In this work, the Cat II and Cat III thresholds were used to assess the measured indoor temperatures.[7] The percentage of hours inside and outside each threshold during the occupied period (as defined above) was calculated for every living room and bedroom. Rooms with more than 5% of hours below the lower threshold or above the upper thresholds were then analysed further.

3. Results

3.1. *Average temperatures*

The temperatures during the occupied hours in the living rooms and bedrooms averaged across all 193 free-floating homes were consistent with thermal comfort expectations; in the living rooms the mean temperature during the occupied hours varied from 18.9 °C to 25.7 °C, with an average across all homes of 21.8 °C.[8] The mean bedroom temperatures during occupied hours were very similar, varying from 18.7 °C to 25.8 °C, with an average of 21.6 °C (Table 2). Whilst the average maximum temperatures were not unduly high, 25.7 °C in the living rooms and 25.4 °C in the bedrooms (Table 2), individual dwellings had living room and bedrooms temperatures up to 30.3 °C.

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[5] CIBSE Guide A [19] defines free-running as "a mode of operation of a building rather than a specific building type". The Guide continues "A building can be said to be free-running when it is not, at the time in question, consuming energy for the purpose either of heating or of cooling".

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

[7] The BSEN15251 lower thresholds are only defined down to a T_{rm} value of 15 °C so, in keeping with previous work, it was presumed that they run horizontally for $T_{\mathrm{rm}} < 15$ °C.

[8] Calculated as the mean of the average hourly temperature during the occupied hours for the 41 day monitoring period.

Table 2
Average mean and maximum living room and bedroom temperatures and 95% confidence intervals by the built type, age band, external wall type and Government Office Region.

Dwelling categories	Living room (08:00–22:00)		Bedroom (23:00–07:00)	
	Mean temperature[a] (°C) (95% CI)[c]	Average maximum[b] temperature (°C) (95% CI)	Mean temperature[a] (°C) (95% CI)	Average maximum[b] temperature (°C) (95% CI)
All dwellings (n = 193)	21.8 (21.6, 22.0)	25.7 (25.4, 25.9)	21.6 (21.4, 21.8)	25.4 (25.0, 25.7)
By built type				
Detached ($n = 66$)	***21.5*** (21.1, 21.8)	***25.4*** (24.9, 25.9)	***21.1*** (20.7, 21.4)	***24.8*** (24.0, 25.7)
Semi-detached ($n = 64$)	21.7 (21.4, 22.0)	25.5 (25.0, 25.9)	21.7 (21.4, 22.1)	25.6 (25.2, 26.0)
End terrace ($n = 14$)	21.7 (21.0, 22.5)	25.9 (25.1, 26.8)	**22.1** (21.5, 22.7)	**26.2** (25.6, 26.8)
Mid terrace ($n = 29$)	21.9 (21.5, 22.4)	25.7 (25.1, 26.4)	21.9 (21.5, 22.4)	25.6 (25.0, 26.3)
Flat[d] ($n = 19$)	**22.8** (22.1, 23.4)	**27.1** (26.1, 28.1)	22.0 (21.3, 22.8)	25.50 (24.7, 26.3)
By building age band				
Pre 1919 ($n = 23$)	***20.8*** (20.2, 21.5)	***24.3*** (23.5, 25.1)	***20.6*** (19.9, 21.4)	***23.3*** (20.9, 25.6)
1919–1944 ($n = 34$)	22.0 (21.5, 22.4)	**26.1** (25.5, 26.7)	21.6 (21.1, 22.0)	25.6 (25.0, 26.1)
1945–1964 ($n = 50$)	21.8 (21.4, 22.2)	25.8 (25.2, 26.3)	21.6 (21.1, 22.0)	25.4 (25.0, 25.8)
1965–1980 ($n = 47$)	21.8 (21.4, 22.1)	25.8 (25.3, 26.3)	21.5 (21.1, 21.8)	25.5 (25.1, 25.8)
1981–1990 ($n = 19$)	22.0 (21.4, 22.7)	25.9 (25.2, 26.6)	22.1 (21.5, 22.6)	25.7 (25.0, 26.5)
Post 1990 ($n = 20$)	**22.3** (21.8, 22.8)	26.0 (25.0, 27.1)	**22.6** (22.1, 23.2)	**26.7** (26.0, 27.4)
By external wall type				
Cavity wall ($n = 119$)	21.8 (21.6, 22.1)	25.7 (25.4, 26.1)	**21.7** (21.5, 22.0)	**25.7** (25.4, 26.0)
Solid brick ($n = 51$)	21.9 (21.6, 22.2)	**25.9** (25.4, 26.4)	21.6 (21.3, 22.0)	25.5 (25.2, 25.8)
Solid stone ($n = 8$)	***20.2*** (18.7, 21.8)	***23.6*** (21.9, 25.3)	***20.1*** (18.4, 21.8)	***23.3*** (21.2, 25.3)
Timber frame ($n = 7$)	**22.0** (19.2, 24.8)	25.7 (21.5, 29.9)	21.4 (18.5, 24.1)	24.9 (21.8, 27.9)
By Government Office Region				
North East ($n = 13$)	***20.8*** (19.9, 21.8)	***24.0*** (22.9, 25.1)	***20.3*** (19.4, 21.3)	***23.6*** (22.3, 24.9)
West Midlands ($n = 26$)	21.7 (21.1, 22.2)	25.7 (25.0, 26.4)	21.4 (20.8, 22.0)	25.5 (24.8, 26.1)
Yorkshire ($n = 10$)	21.1 (20.2, 22.0)	25.2 (24.7, 25.8)	21.4 (20.5, 22.3)	25.5 (24.7, 26.4)
South West ($n = 29$)	21.7 (21.2, 22.3)	25.2 (24.5, 25.9)	21.9 (21.2, 22.5)	24.6 (22.7, 26.5)
East Midlands ($n = 16$)	**22.4** (21.9, 22.9)	**26.6** (25.9, 27.3)	21.8 (21.1, 22.5)	26.2 (25.5, 26.9)
North West ($n = 24$)	21.4 (20.8, 22.0)	24.9 (24.2, 25.6)	21.4 (20.8, 22.0)	24.8 (24.3, 25.3)
East of England ($n = 30$)	22.1 (21.6, 22.6)	26.2 (25.3, 27.1)	21.9 (21.5, 22.4)	26.2 (25.7, 26.7)
South East ($n = 37$)	22.1 (21.7, 22.5)	26.3 (25.7, 26.9)	21.6 (21.2, 22.0)	25.6 (25.1, 26.1)
London ($n = 8$)	22.2 (21.1, 23.2)	26.4 (25.3, 27.6)	**22.2** (21.2, 23.3)	**26.3** (25.4, 27.1)

For each dwelling category and temperature – smallest values e.g. ***20.8***; largest values e.g. **22.3**.

[a] Calculated as the average of the mean hourly air temperatures for the particular dwelling category.

[b] Calculated as the average of the maximum hourly air temperatures for the particular dwelling category.

[c] 95% Confidence Interval (CI) lower and upper bounds.

[d] Consisted of 16 purpose built flats, 2 converted homes and 1 flat above a commercial building.

The 14 heated homes were scattered across all the GORs with no region having a significantly larger proportion than the others. The mean temperatures were similar to those in the free-running homes: the mean temperatures in the living rooms during occupied hours varied from 19.2 °C to 24.7 °C, with an average mean of 21.9 °C; the mean bedroom temperatures varied from 19.2 °C to 26.2 °C with an average mean of 21.9 °C. The individual dwellings had living room and bedroom temperatures up to 30.6 °C and 33.6 °C respectively.

In the free-running dwellings, there was, overall, no clear tendency for the bedrooms or living rooms to be the warmer. In 86 homes (45%) the average of the hourly bedroom temperatures was up to 3.9 °C higher than the average of the hourly living room temperatures and in 107 homes (55%) the bedroom was up to 4.2 °C warmer than the living room. There were, however, clear underlying patterns in the living room and bedroom temperatures depending on built type, age band, wall type and location.

There was a general trend towards higher mean and maximum internal temperatures in the living room and bedroom as house age decreased (Table 2). Thus modern homes (i.e. built after 1990) had the warmest living rooms and bedrooms on average and pre-1919 homes the coolest. This is likely to be because more modern homes are better insulated than older homes. Considering house type, flats had the warmest living rooms (and almost the warmest bedrooms) whereas detached homes had the coolest. This may well be because flats often have a reduced external wall area to volume ratio whereas in detached homes this ratio is high. Solid stone construction tended to result in lower room temperatures. Overall then, homes that are detached, built before 1919, or with solid stone walls had cooler living rooms and cooler bedrooms than the other homes in the corresponding dwelling category. Regionally, dwellings in the North East had lower living room and bedroom temperatures than homes in any other region of the country, whereas the bedrooms of homes in London were noticeably warmer (Table 2).

3.2. *Assessment using static criteria*

The static criteria indicated that in the 193 homes that were free-running, on average, only 4% of living rooms exceeded the 1%/28 °C threshold during occupied hours (08:00–22:00) whereas, a large proportion of the bedrooms, 21%, exceeded the 1%/26 °C threshold during their occupied hours (23:00–07:00), with 47% exceeding the 5%/24 °C threshold. The high proportion of homes with elevated bedroom temperatures is perhaps surprising given the rather cool external temperatures. It is important to remember though that the average temperature in all the bedrooms wasn't very different from that in all the living rooms, but the temperature thresholds are lower in bedroom criteria.

The number of hours for which the CIBSE thresholds were exceeded varied considerably between the homes studies and this inter-house range was large in most GORs despite the external temperature differences (Figs. 7 and 8). In all GORs the coolest living rooms never reached temperatures over 25 °C (Fig. 7) and, except in London, the coolest bedrooms never exceeded 24 °C

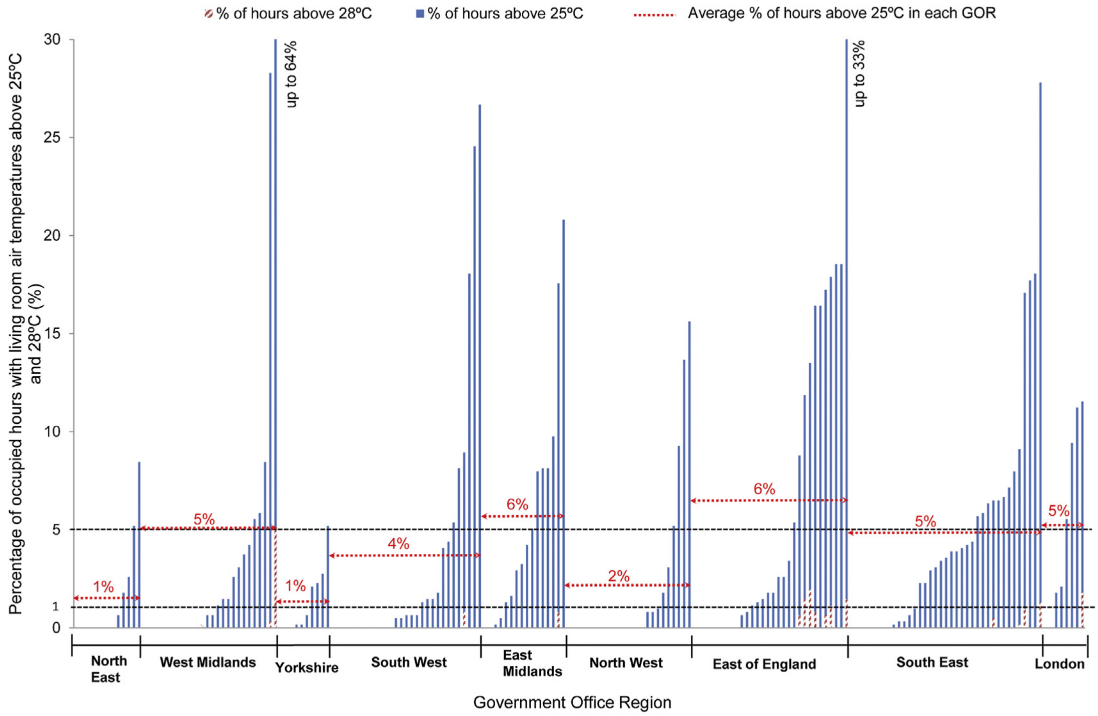

Fig. 7. Percentage of occupied hours (08:00–22:00) in each of 193 free running living rooms with an air temperature above 25 °C and 28 °C for each Government Office Region. (Regions are ordered from lowest average hourly external air temperature (left) to highest (right) and within each region homes are ranked by hours over 25 °C).

(Fig. 8). Some homes were however very warm, the warmest living room had 64% of occupied hours over 25 °C (Fig. 7) and the warmest bedroom 86% of hours over 24 °C, with one bedroom having just under 50% of hours over 26 °C (Fig. 8).

As measured by the average percentage of occupied hours for which living rooms exceeded 25 °C (Fig. 7) and bedrooms exceeded 24 °C (Fig. 8), the warmer homes were in the London, the South East, the East, the East Midlands, and the West Midlands, whereas

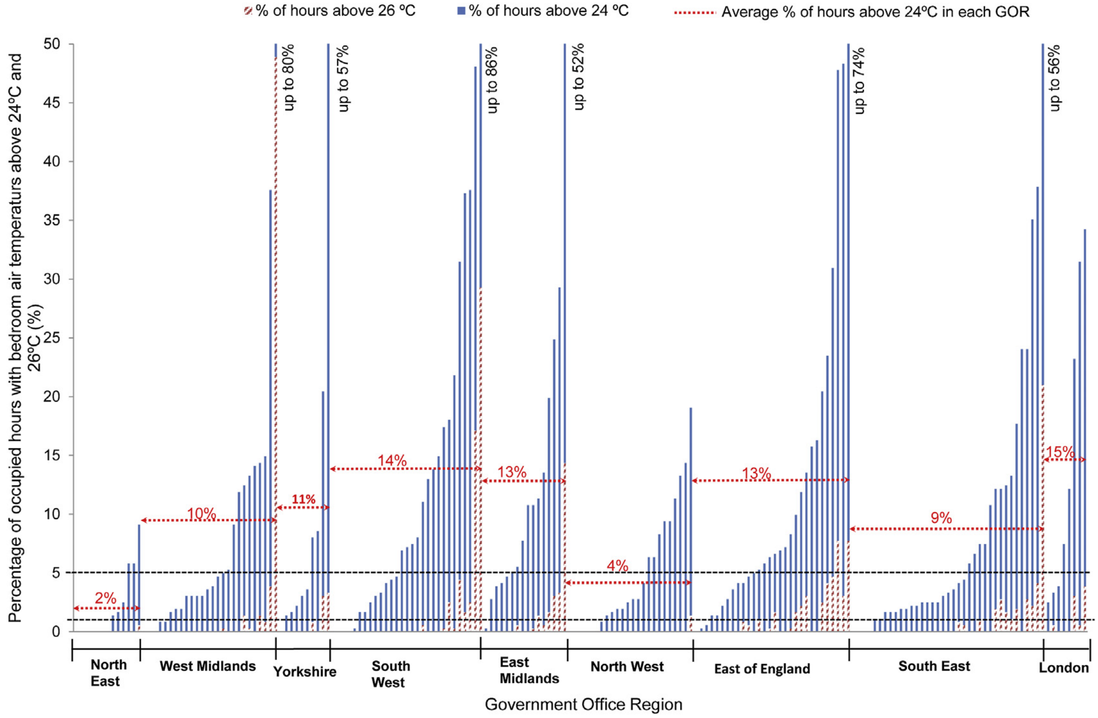

Fig. 8. Percentage of occupied hours (23:00–07:00) in each of 193 free running bedrooms with an air temperature above 24 °C and 26 °C for each Government Office Region. (Regions are ordered from lowest average hourly external air temperature (left) to highest (right) and within each region homes are ranked by hours over 24 °C).

Table 3
Percentage of living rooms and bedrooms which exceeded the static criteria and average percentage of hours above temperature thresholds by built type, age band, external wall type and Government Office Region.

Dwelling categories	Living room (08:00–22:00)		Bedroom (23:00–07:00)	
	Percentage with more than 5% of hours over 25 °C (Average % of hours over 25 °C)	Percentage with more than 1% of hours over 28 °C (Average % of hours above 28 °C)	Percentage with more than 5% of hours over 24 °C (Average % of hours over 24 °C)	Percentage with more than 1% of hours over 26 °C (Average % of hours above 26 °C)
All dwellings ($n = 193$)	27 (4.3)	4 (0.1)	47 (10.1)	21 (1.3)
By built type				
Detached ($n = 66$)	21 (3.6)	3 (0.1)	36 (7.0)*	16 (1.1)
Semi-detached ($n = 64$)	22 (4.2)	2 (0.1)	45 (11.1)	22 (1.9)
End terrace ($n = 14$)	21 (2.3)	7 (0.1)	71 (13.5)**	14 (0.7)
Mid terrace ($n = 29$)	28 (3.9)	3 (0.1)	48 (11.8)	28 (1.2)
Flat ($n = 19$)	68 (9.1)**	10 (0.3)*	74 (12.2)	32 (1.0)
By building age band				
Pre 1919 ($n = 23$)	13 (1.1)*	0 (0.0)	17 (3.8)**	4 (0.9)**
1919–1944 ($n = 34$)	35 (6.8)	3 (0.3)**	47 (9.4)	23 (1.2)
1945–1964 ($n = 50$)	28 (4.4)	2 (0.1)	50 (10.2)	14 (1.7)
1965–1980 ($n = 47$)	25 (4.2)	2 (0.1)	45 (8.1)	21 (0.5)
1981–1990 ($n = 19$)	31 (3.8)	0 (0.0)	42 (11.8)	21 (1.3)
Post 1990 ($n = 20$)	30 (4.6)	5 (0.2)	80 (21.0)**	55 (3.1)**
By external wall type				
Cavity wall ($n = 119$)	27 (4.5)	4 (0.1)	53 (11.3)**	25 (1.6)**
Solid brick ($n = 51$)	31 (4.6)	4 (0.1)	41 (9.0)	16 (0.9)
Solid stone ($n = 8$)	12 (1.1)	0 (0.0)	12 (3.1)**	0 (0.0)
Timber frame ($n = 7$)	29 (5.4)	0. (0.0)	43 (9.4)	14 (0.6)
By Government Office Region				
North East ($n = 13$)	15 (1.4)	0 (0.0)	23 (2.0)*	0 (0.0)*
West Midlands ($n = 26$)	19 (5.1)	4 (0.2)	38 (9.6)	15 (2.2)
Yorkshire and the Humber ($n = 10$)	10 (1.3)	0 (0.0)	40 (10.5)	20 (0.8)
South West ($n = 29$)	21 (3.8)	0 (0.0)	55 (14.0)	21 (2.6)
East Midlands ($n = 16$)	44 (5.7)	0 (0.0)	62 (12.9)	31 (1.6)
North West ($n = 24$)	17 (2.1)	0 (0.0)	37 (4.1)	4 (0.1)**
East of England ($n = 30$)	37 (6.5)	13 (0.3)**	60 (13.0)	37 (1.4)
South East ($n = 37$)	15 (4.9)	3 (0.1)	40 (8.8)	27 (1.1)
London ($n = 8$)	50 (5.2)	12 (0.2)	62 (14.8)	25 (1.0)

Significant results $^{**}p < 0.05$, $^{*}p < 0.1$.

the cooler homes were to be in the North East, North West and Yorkshire.[9] Chi-squared tests (Table 3), indicated that there were significantly fewer bedrooms in the North West with more than 1% of occupied hours over 26 °C than bedrooms in other regions (4% cf. 21% for all the dwellings, $p < 0.05$) and there were significantly more living rooms in the East of England with more than 1% of occupied hours over 28 °C than living rooms in other regions (13% cf. 4% for all the dwellings, $p < 0.05$).

Pooling all the results for the free-running living rooms (Fig. 9) and the free-running bedrooms (Fig. 10) provides an impression on the variability of temperatures across the whole sample of English homes. The variation between homes is clear as, comparing Figs. 9 and 10, there is a clear tendency for bedrooms to exceed the relevant thresholds (24 °C and 26 °C) than the living rooms to exceed their relevant threshold (25 °C and 28 °C).

Considering the impact of dwelling type, age and wall type (Table 3), it is evident that significantly more living rooms in flats exceeded the 5%/25 °C criterion (68%, $p < 0.05$) than in other dwelling types (within which 22% of living room exceeded the 5%/25 °C criterion). Significantly more living rooms in flats also exceeded the 1%/28 °C criterion (10%, $p < 0.1$) than in other dwelling types. Within this relatively small sample of 19 flats, there was a tendency for more of the top-floor living rooms to exceed the relevant thresholds than the rooms in flats on lower levels (Table 4). The tendency for flats, especially top floor flats, to be warmer than other house types is consistent with others' findings (see Discussion section).

Significantly fewer detached homes (36%) had bedroom temperatures that exceeded the 5%/24 °C criterion than did other dwelling types ($p < 0.1$), which might be due to the tendency of these homes to have a greater external wall area through which heat can be lost. Curiously, end-terraces had significantly more bedrooms (71%) that exceeded the 5%/24 °C criterion ($p < 0.05$), but it is not so obvious why this should be so.

In older homes (pre 1919), which in England would have been built with solid, uninsulated walls and no cavity, significantly fewer bedrooms (17%, $p < 0.05$) and living rooms (13%, $p < 0.1$) exceeded the 5%/24 and 5%/25 criteria respectively than did the younger homes. Significantly, more bedrooms in modern, post-1990, homes, which would have well insulated cavity walls, exceeded both criteria than in older homes ($p < 0.05$). The results are striking, as despite the cool summer, 80% of bedrooms in post-1990 homes exceeded the 5%/24 °C criterion and 55% the 1%/26 °C criterion. The results for external wall type are consistent with this result, as significantly more homes with cavity walls had bedrooms that exceeded 5%/24 °C (53%, $p < 0.05$) and 1%/26 °C (25%, $p < 0.05$) criteria than did homes with other wall types. Significantly fewer bedrooms in homes with solid stone walls exceeded the 5%/24 °C criterion (12%, $p < 0.05$).

Taken together these results corroborate the observations made based on the average measured temperatures (Section 3). Homes which are likely to have lower fabric heat loss, i.e. modern homes, flats, and homes with cavity walls tend to have warmer bedrooms or living rooms and those that are likely to have higher fabric heat loss, detached homes, older homes and, perhaps, those with solid stone walls tend to have cooler bedroom.

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[9] Ignoring the single very warm bedroom in Yorkshire.

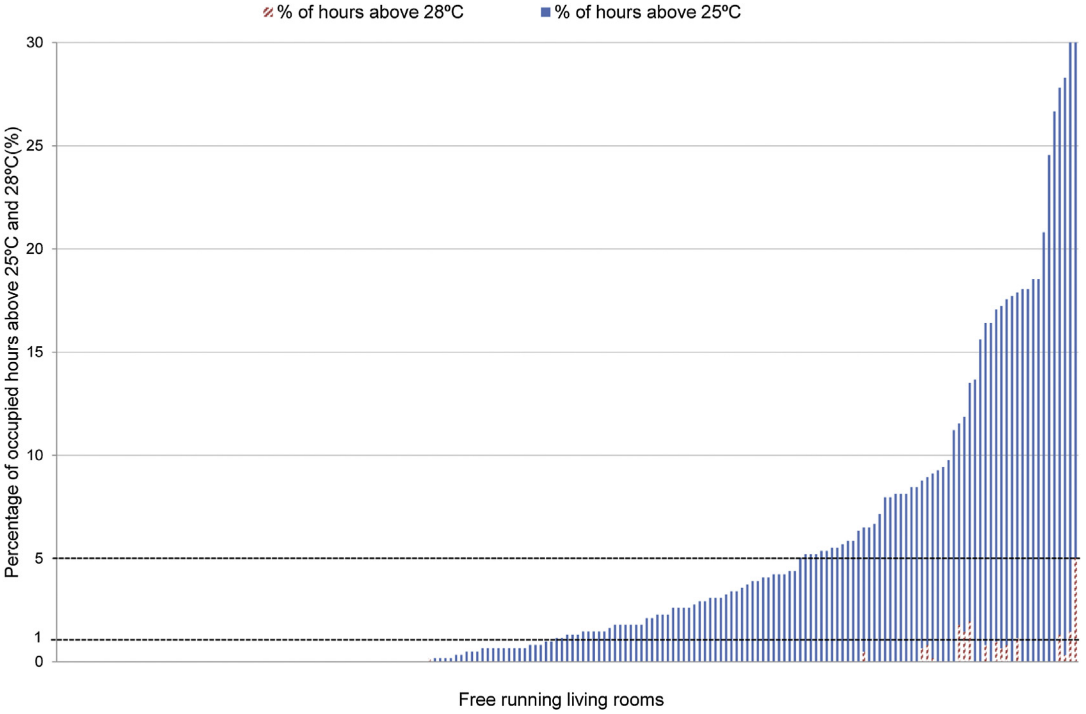

Fig. 9. Percentage of hours with measured air temperatures over 25 °C and 28 °C in all 193 free-running living rooms (ranked by hours over 25 °C from lowest (left) to highest (right)).

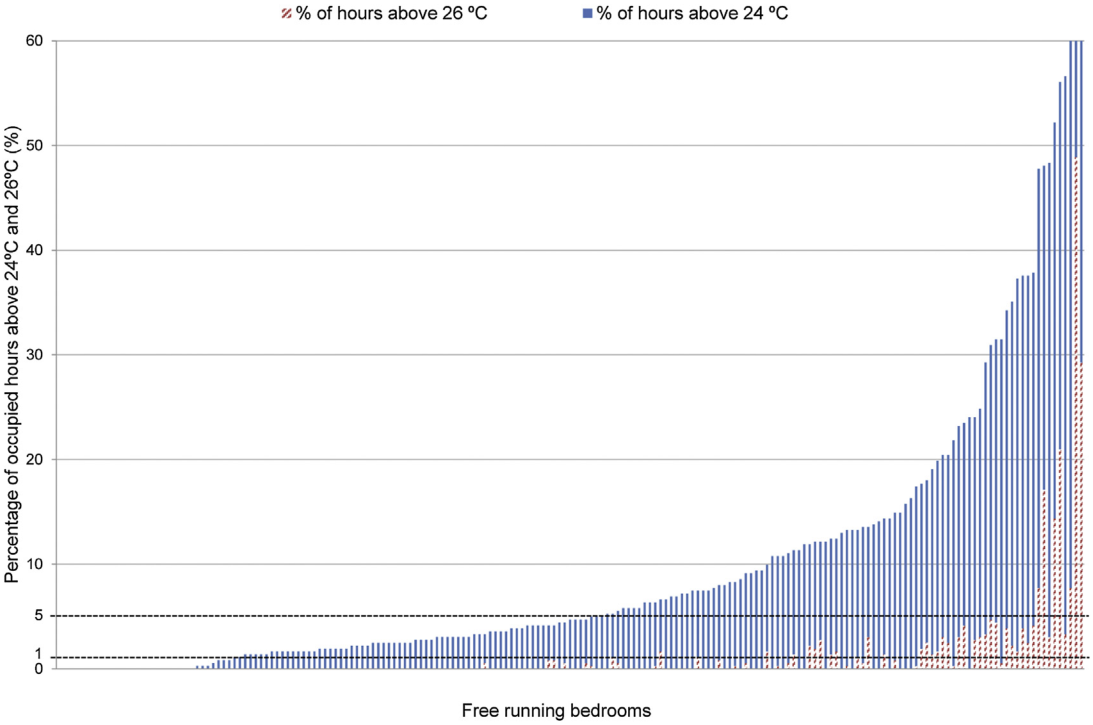

Fig. 10. Percentage of hours with measured air temperatures over 24 °C and 26 °C in all 193 free-running bedrooms (ranked by hours over 24 °C from lowest (left) to highest (right)).

Table 4
Average percentage of occupied hours above threshold criteria, by level of flat.

Level of flat (Number in sample)	Living room (08:00–22:00)		Bedroom (23:00–07:00)	
	Number with more than 5% of hours over 25 °C (Average % of hours above 25 °C)	Number with more than 1% of hours over 28 °C (Average % of hours above 28 °C)	Number with more than 5% of hours over 24 °C (Average % of hours above 24 °C)	Number with more than 1% of hours over 26 °C (Average % of hours above 26 °C)
Basement ($n = 2$)	2 (5.5)	0 (0.0)	1 (4.7)	0 (0.0)
Ground floor ($n = 6$)	4 (7.2)	0 (0.2)	4 (10.8)	1 (0.3)
Mid floor ($n = 4$)	1 (3.7)**	0 (0.1)	2 (6.1)	2 (0.7)
Top floor ($n = 7$)	6 (15.0)	2 (0.6)**	5 (19.0)	3 (1.9)

Significant results $^{**}p < 0.05$, $^{*}p < 0.1$.

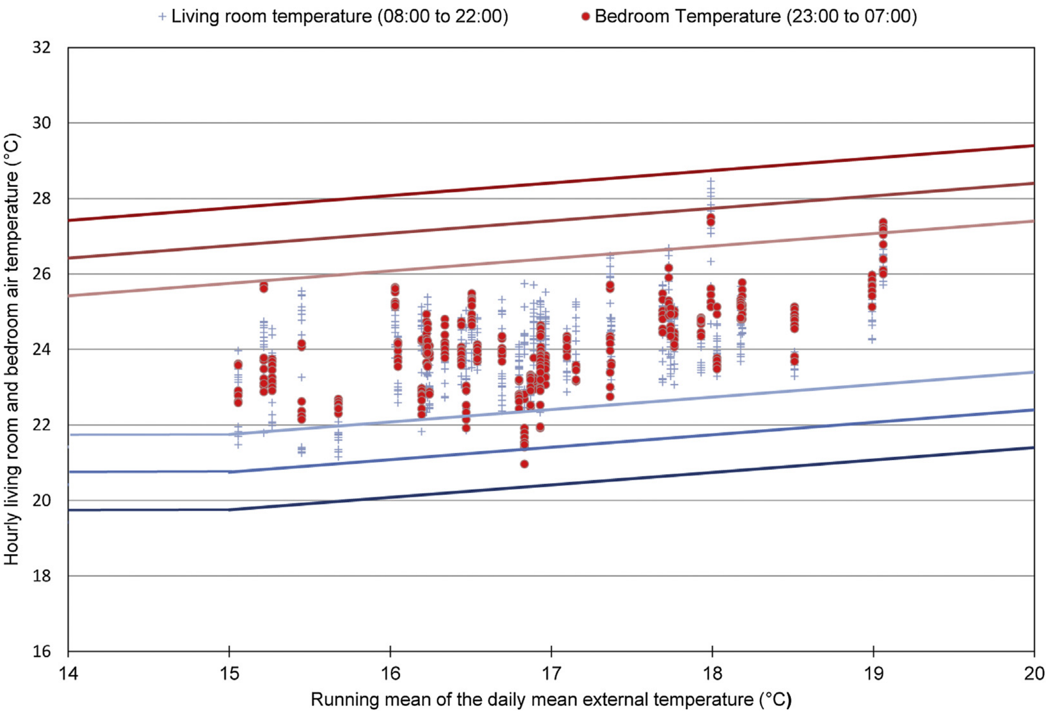

Fig. 11. Air temperatures measured in a warmer home in the London Government Office Region and the BSEN15251 thresholds.

3.3. *Thermal comfort and overheating risk assessment using BSEN15251 (adaptive approach)*

To evaluate the internal temperatures in the dwellings using the BSEN15251 adaptive standard, the hourly living room and bedroom temperatures were plotted against the exponentially weighted running mean of the daily mean external temperature (T_{rm}) for all 193 free-running dwellings. Two such plots are shown here, one for a warmer home located in London (Fig. 11) and one for a cooler home in the North East (Fig. 12).

For each value of T_{rm}, there is a vertical string of 24 hourly data points nine for the night time bedroom temperatures and 15 for the day and evening time living room temperatures. The plots illustrate the different temperatures found in different homes at the same T_{rm} value and also the general tendency, found across the sample, for the indoor temperatures to increase as the T_{rm} value increases. Whilst the warmer home exceeded the Cat II upper threshold on one day, for the majority of the time the temperatures were within the Cat I boundaries. In contrast the cooler home frequently experiences indoor temperatures below even the Cat III threshold, which suggests, according to the BSEN15251 standard that it is uncomfortably cool.

To investigate further, the percentage of all hours for which the measured temperatures were within each category were calculated and plotted, in the manner suggested in BSEN15251, for the living rooms (Fig. 13) and the bedrooms (Fig. 14).[10] It is immediately apparent that in all GORs, the living room temperatures were within the Cat I thresholds for much of the time (46% of occupied hours on average) and that the upper category thresholds, which indicate warm discomfort, were rarely exceeded. In contrast, there were many living rooms that had temperatures below the Cat III lower threshold for much of the time (moderate expectations, applicable to existing buildings). In the sample as a whole, living rooms were, on average, below the Cat III envelope for 14% of the time. Furthermore, 50% of living rooms had more than 5% of occupied hours below the Cat III threshold; 5% is a BSEN15251 suggested limit of acceptability. Bedrooms were also rather cool, 52% of bedrooms had more than 5% of occupied hours below the Cat III threshold and, in the sample as a whole, there were, on average, 17% of bedroom occupied hours below the Cat III threshold. Clearly,

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[10] Data are ordered from left to right for each GOR by the percentage of hours within the Cat I boundaries.

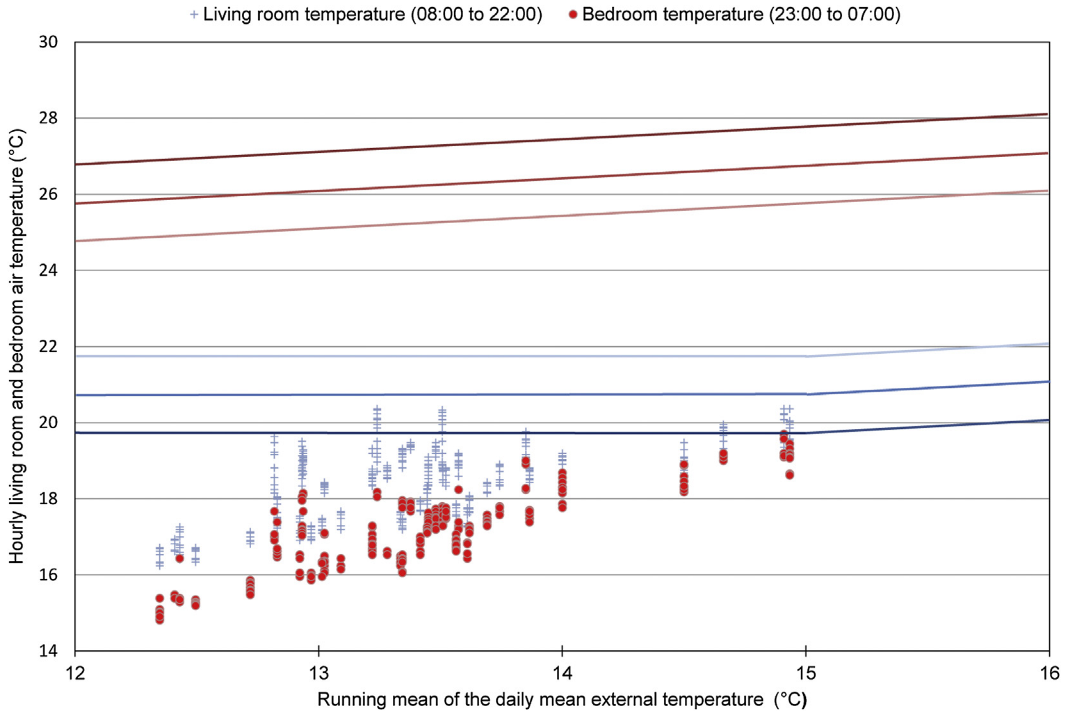

Fig. 12. Air temperatures measured in a cooler home in the North East Government Office Region and the BSEN15251 thresholds.

many English households choose living room and bedroom temperatures that do not conform to the expectations of BSEN15251.

Within the general trend towards cool temperatures, there were significantly more living rooms and bedrooms in detached homes (64% and 67% respectively) and homes built before 1919 (both 70%) with more than 5% of occupied hours below the Cat III threshold than in other house type and age ($p < 0.05$) (Table 5). In contrast, there were significantly fewer living rooms and bedrooms in flats (21% and 32% respectively) and bedrooms in homes built after 1990 (30%) with more than 5% of occupied hours below the Cat III lower

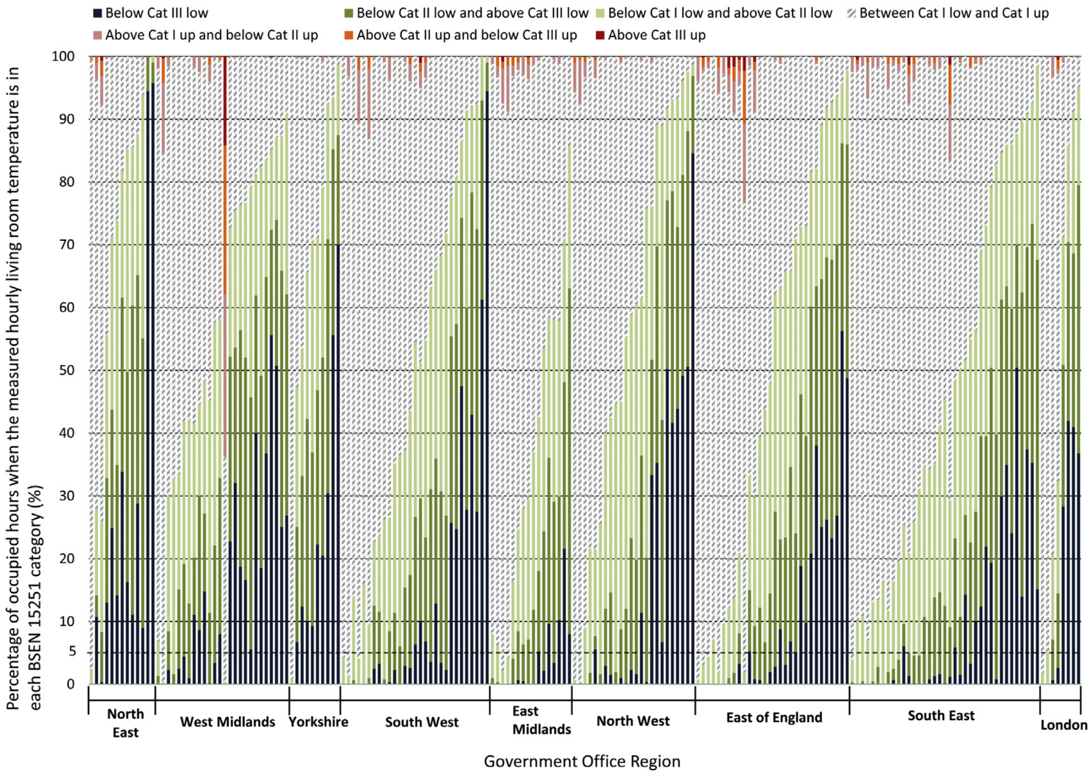

Fig. 13. Percentage of occupied hours when the measured hourly living room air temperature is in each BSEN15251 thermal comfort category.

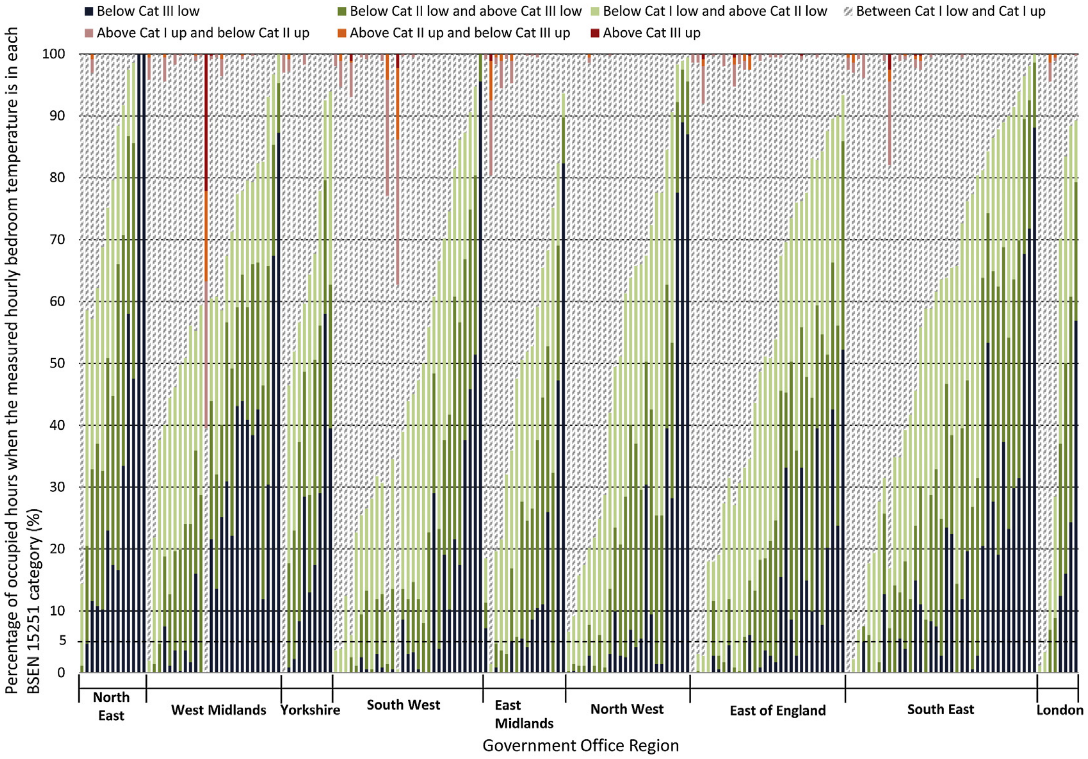

Fig. 14. Percentage of occupied hours when the measured hourly bedroom air temperature is in each BSEN15251 thermal comfort category.

Table 5
Percentage of homes with more than 5% of occupied hours below the BSEN15251 Cat II and Cat III thresholds by built type, age band, external wall type and Government Office Region.

Dwelling categories	Living room (08:00–22:00)		Bedroom (23:00–07:00)	
	Percentage with more than 5% hours below Cat II[a] (Average % of hours below Cat II)	Percentage with more than 5% hours below Cat III (Average % of hours below Cat III)	Percentage with more than 5% hours below Cat II[a] (Average % of hours below Cat II)	Percentage with more than 5% hours below Cat III (Average % of hours below Cat III)
All dwellings ($n = 193$)	72 (17)	50 (14)	76 (17)	52 (17)
By built type				
Detached ($n = 66$)	77 (19)	64 (19)**	86 (20)*	67 (24)**
Semi-detached ($n = 64$)	80 (19)	48 (13)	78 (17)	47 (15)
End terrace ($n = 14$)	79 (14)	50 (14)	71 (12)	36 (10)
Mid terrace ($n = 29$)	65 (18)	41 (9)	69 (18)	48 (10)
Flat ($n = 19$)	37 (6)**	21 (8)**	47 (10)**	32 (11)*
By building age band				
Pre 1919 ($n = 23$)	78 (23)	70 (29)**	83 (21)	70 (29)**
1919–1944 ($n = 34$)	73 (18)	62 (13)	88 (18)*	62 (17)
1945–1964 ($n = 50$)	74 (18)	42 (13)	82 (17)	46 (18)
1965–1980 ($n = 47$)	72 (17)	53 (13)	74 (17)	55 (18)
1981–1990 ($n = 19$)	68 (13)	32 (11)*	63 (17)	42 (6)
Post 1990 ($n = 20$)	60 (13)	40 (7)	50 (10)**	30 (5)**
By external wall type				
Cavity wall ($n = 119$)	71 (17)	48 (13)	76 (16)	50 (15)
Solid brick ($n = 51$)	76 (18)	45 (11)	78 (19)	51 (14)
Solid stone ($n = 8$)	75 (22)	87 (43)**	75 (15)	75 (42)
Timber frame ($n = 7$)	57 (17)	86 (13)*	71 (19)	71 (21)
By Government Office Region				
North East ($n = 13$)	77 (21)	85 (27)**	77 (23)	85 (33)**
West Midlands ($n = 26$)	85 (19)	61 (16)	85 (18)	61 (21)
Yorkshire and the Humber ($n = 10$)	90 (24)	90 (24)**	90 (21)	70 (20)
South West ($n = 29$)	72 (16)	41 (14)	65 (13)	34 (12)**
East Midlands ($n = 16$)	69 (14)	31 (4)	69 (15)	50 (13)
North West ($n = 24$)	71 (16)	46 (18)	71 (15)	42 (17)
East of England ($n = 30$)	67 (17)	47 (11)	73 (17)	43 (11)
South East ($n = 37$)	62 (15)	40 (9)	40 (18)	57 (17)
London ($n = 8$)	75 (17)	50 (19)	75 (17)	50 (14)

Significant results **$p < 0.05$, *$p < 0.1$.
[a] Below Cat II lower limit and above Cat III lower limit.

Table 6
Statistical analysis of free-running flats by the flat level using adaptive thermal comfort criteria of BSEN15251.

Level of flat	Living room (08:00–22:00)		Bedroom (23:00–07:00)	
	Number with more than 5% hours below Cat II[a]	Number with more than 5% hours below Cat III	Number with more than 5% hours below Cat II[a]	Number with more than 5% hours below Cat III
Basement ($n = 2$)	1	0	2	0
Ground floor ($n = 6$)	1	1	1*	1
Mid floor ($n = 4$)	3*	2	2	1
Top floor ($n = 7$)	2	1*	4	4

Significant results **$p < 0.05$, *$p < 0.1$.
[a] Below Cat II lower limit and above Cat III lower limit.

threshold than homes of other type and age. Within the flats, there were significantly fewer living rooms in top floor flats with more than 5% of hours below the Cat III than on other floors (only 1 out of 7, $p < 0.1$) (Table 6). However, the sample size was too small to be able to draw robust conclusions. As a group, these results are consistent with those obtained using the static criteria (Section 3.2).

Homes in Yorkshire and Humberside and the North East tended to have more hours below the Cat III, than homes in other regions (Table 5). This might seem logical, given the rather cool nature of these regions, but since the adaptive standard accounts for the regional differences in temperature (the T_{rm} values differ), it might actually be an indication that households in these regions are even more 'tolerant' of cool temperatures than the households in warmer regions.

4. Discussion

4.1. Summer indoor temperatures and thermal comfort in free-running English homes

The results of this work, which is one of the first national scale studies of summertime temperatures and thermal comfort, are worth reflecting on. In particular, to consider the extent to which they do, or do not, concur with the results of others. In this regard the study of temperatures in homes in the city of Leicester [12] is particularly pertinent as it also consisted of a large sample of homes (230 free-running, cf. 193 in this work), used the same field monitoring techniques, and the data was analysed in the same way.

The principle differences lie on the sample composition and the weather conditions (Table 7). Compared to this study, the Leicester sample contained a higher proportion of semi-detached and terraced houses and far fewer detached houses (9% compared to 34% in this work); these differences are to be expected of a typical UK city. The summer of 2009, during which the Leicester homes were monitored (mean temperature 16.4 °C), was much warmer than the national average temperature during this study in 2007 (15.3 °C across all GORs) and more importantly, the Leicester data included a hot period of 5 days during which the average temperature on one day was 24.1 °C. Not surprisingly therefore, average mean temperatures for the living rooms and bedrooms in the Leicester study (22.2 °C and 22.4 °C respectively) were higher than in this study (21.8 °C and 21.6 °C respectively) (Table 7). The frequency of occurrence of elevated temperatures in the Leicester study was also higher: 89% of bedrooms exceeded the 1%/26 °C criterion compared to 21% in this work (which is nevertheless, especially given the cool conditions, a high proportion) and 27% of living rooms exceeded the 1%/28 °C criterion compared to just 4% on this study (Table 7). In the Leicester study there were 58% of the living rooms and 93% of the bedrooms that exceeded the 5%/25 °C and 5%/24 °C criteria respectively, compared to 27% of the living rooms and 47% of the bedrooms in this study (Table 7).

Considering the BSEN15251 thermal comfort standard, in this study there were slightly more living rooms and bedrooms with more than 5% of occupied hours below the Cat II and Cat III thresholds than in the Leicester City Study (Table 7). As the adaptive standard seeks to account for the differences in external temperatures (the T_{rm} values differ between the two studies), this might be due to differences in the proportion of house types in the two samples (e.g. far fewer detached homes in the Leicester sample which tend to be the coolest built type) and/or an indication of a difference between the tolerance to cool temperatures of households in some GORs compared to households in Leicester (see Section 3.3).

Despite the differences between the two studies, some underlying and significant differences in the temperatures in homes of different type, age and construction were common to both datasets. In both studies a significantly higher percentage of detached homes had living rooms with more than 5% of hours below BSEN15251 Cat III lower threshold (64% in this study & 56% in the Leicester study [12], $p < 0.05$). In contrast, both studies

Table 7
Comparison of two studies of summertime temperatures in English homes.

	Beizaee and Lomas et al.	Lomas and Kane [12]
Sampling region	England	Leicester City
Sample size	207 homes	264 homes
Sampling period	22nd July to 31st August	1st July to 31st August
Sampling duration	41 days	62 days
Rooms monitored	Living room and main bedroom	
Percentage heated	7%	13%
Number of free-running homes	193	230
Average external temperature	15.3 °C	16.4 °C
Average living room temperature	21.8 °C	22.2 °C
Average bedroom temperature	21.6 °C	22.4 °C
Living rooms with more than 5% occupied hours over 25 °C	27%	58%
Living rooms with more than 1% occupied hours over 28 °C	4%	27%
Bedrooms with more than 5% occupied hours over 24 °C	47%	93%
Bedrooms with more than 1% occupied hours over 26 °C	21%	89%
Living rooms with more than 5% of occupied hours below BSEN15251 Cat II threshold	72%	64%
Bedrooms with more than 5% of occupied hours below BSEN15251 Cat II threshold	76%	71%
Living rooms with more than 5% of occupied hours below BSEN15251 Cat III threshold	50%	34%
Bedrooms with more than 5% of occupied hours below BSEN15251 Cat III threshold	52%	49%

showed that flats (especially top floor flats) are the dwelling type with the highest temperatures: in both studies there were significantly more living rooms in flats that exceeded both the 5%/25 °C and 1%/28 °C criterion (68% and 10% respectively in this study & 74% and 48% in Leicester study [12], $p < 0.1$); and in both studies there were significantly fewer living rooms (37% and 21% in this study & 48% and 15% in Leicester study [12]) and bedrooms (47% and 32% in this study & 52% and 19% in Leicester study [12]) in flats with more than 5% of hours below the Cat II and Cat III thresholds ($p < 0.1$). This study indicated that top floor flats were particularly warm compared to flats on other floors: significantly more living rooms in top floor flats exceeded the 1%/28 °C criterion (2 out of 7, $p < 0.05$) and significantly fewer of them had more than 5% of hours below the BSEN15251 Cat III lower threshold (only 1 out of 7, $p < 0.1$). These observations about temperatures in flats are consistent with the findings of previous summertime temperature monitoring studies, e.g. by Mavrogianni et al. [8,26], as well as previous modelling studies, e.g. Oikonomou et al. [28]. Further the results align with remarks in the national heat wave plan [29]; that top floor flats are particularly at overheating risk.

The tendency for higher indoor temperatures in flats and lower indoor temperatures in detached homes could be explained by the differences in their external surface to floor area ratio. Detached homes have a relatively high external surface to floor area ratio whereas for flats this ratio is relatively small. This can have at least two consequences. Firstly, because in England, the summertime external temperature is often lower than indoor comfort temperatures, free-running homes with a higher external surface to floor area ratio will, for the same construction (i.e. the same overall U-value), tend to cool down more by conductive heat loss than homes with a lower ratio. Related to this, flats may be bounded by other flats, rather than the ground, which can act as a heat sink. Secondly, a higher external surface to floor area ratio means that cool air ingress by infiltration rates is likely to be higher, as is cool air ingress due to positive ventilation by opening windows. In fact, the reduced potential for ventilation cooling by window opening in flats, especially by cross ventilation, can compromise occupant's attempts to ameliorate uncomfortably high indoor temperatures. The work presented here, and by others, suggests that flats needed to be prioritised when considering climate adaptation measures for summertime overheating and the potential impacts of energy efficient refurbishment of flats given careful thought.

Considering the effects of dwelling construction, both the Leicester study and this work found that: the temperatures in homes with solid wall were significantly lower than in other homes, as indicated by the percentage of living rooms with more than 5% of hours below the Cat III lower threshold (42% and 87% respectively, $p < 0.1$); and that the oldest homes (pre-1919), which invariably have solid brick or stone walls, had also a significantly higher percentage of living rooms with more than 5% of hours below the Cat III lower threshold (61% and 70% respectively, $p < 0.05$). These results may well be because external solid walls have a higher U-value than cavity walls and because solid masonry, which in older homes also forms the internal room walls, result in higher exposed thermal mass. The higher U-values enable excess internal heat to be lost more readily, and the thermal mass will cause internal air temperatures to respond slowly to external temperature variations (and to variations in internal heat gain) so reducing the internal temperature swings. Previous researchers have also found that solid wall construction confers protection against raised internal temperatures [6].

Both this study and the Leicester study showed that the average mean living room and bedroom temperatures were rather similar (and this work also showed that the average maximum temperatures were similar). In consequence, because the chosen static temperature thresholds for bedrooms (5%/24 °C and 1%/26 °C) are lower than those for living rooms (5%/25 °C and 1%/28 °C), in both studies, more bedrooms than living rooms exceed the relevant temperature thresholds; which is consistent with previous findings [27]. The matter of bedroom temperatures is of concern and more work needs to be done to understand what temperatures are not acceptable and how homes might be designed to ensure that acceptable temperatures can be achieved.

This study found that, compared to older dwellings, those built after 1990 had a significantly higher percentage of bedrooms that exceeded the 5%/24 °C and 1%/26 °C criteria (80% and 55% respectively, $p < 0.05$) and significantly fewer such homes had more than 5% of hours below the Cat II and Cat III thresholds (50% and 30%, $p < 0.05$). In contrast, the Leicester study found that the bedrooms of homes built after1980 were significantly cooler, as judged by both static criteria (but there was no significant difference when considering the BSEN15251 adaptive criteria). One may speculate about the reasons for this difference, one may be the difference in the house ages studied (post-1990 cf. post-1980), another might be due to sampling effects in this work and a third might be that whilst modern, well insulated and air tight homes minimise heat loss in cooler summers (this work) they protect against elevated internal temperatures during spells of hot weather (the Leicester study). More field measurement work is needed on the impact of improved insulation and air tightness standards on internal summertime temperatures.

4.2. The reliability of the BSEN15251 adaptive thermal comfort assessment method

The BSEN15251 analysis of temperatures showed that, in contrast to suggestions from static criteria, there was only a very small percentage of the UK dwellings with elevated temperatures during the monitoring period, in fact, most homes were judged as uncomfortably cool (50% of the living rooms and 52% of bedroom temperatures had more than 5% of hours below the Cat III lower threshold). This is similar to the finding of the Leicester study where 34% of living rooms and 49% of bedrooms had more than 5% of hours below the Cat III lower threshold. Other monitoring studies have found similar results. Pimbert and Fishman [30] showed lower neutral[11] temperatures in UK houses, of up to 2 °C compared to offices, and Cena et al. [31] also found a much lower neutral temperatures in houses (21.1 °C) than offices (23.8 °C). Karjalainen [32], by studying the use of thermostat in Finish homes and offices, concluded that people are more tolerant of both lower and higher temperatures in homes than offices as they have more control on their thermal environment. These accumulated results suggest that households in different counties tend to operate their homes such that the internal temperatures are lower than those that BSEN15251 would deem to be thermally comfortable. This brings into question the reliability of the standard for assessing thermal comfort in occupied homes.

BSEN15251 was primarily developed using data from, and to assess thermal comfort in, office environments, which have a mix of occupants with different thermal comfort perceptions and limits on the thermal adaptive actions that may be undertaken [33]. In contrast, the range of adaptive actions which might be undertaken by the occupants in residential buildings is much larger than in offices (changing activity, shifting from one room to another,

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[11] Neutral temperature defines as the temperature at which the person would feel thermally comfortable.

adapting clothing freely, opening windows, drinking cold or warm drinks, snuggling in padded chairs, sitting in sunlight, taking afternoon siestas, etc.). Baker and Standeven [34], de Dear and Brager [35] and Nicol and Humphrey [36] discussed ranges of adaptive actions which may be taken by the occupants in free running dwellings and how significantly they would affect their thermal comfort. These adaptive opportunities enable the lower temperatures that might naturally occur in unheated homes, compared to offices, to be accommodated (houses have higher fabric and infiltration heat loss rates, are less densely occupied and tend to have fewer active electrical appliances than offices). Further, the occupants of homes invariably have to pay for any energy consumption and so are likely to consider personal thermal adaptation to lower temperatures before, or alongside, use of the heating system; (in this study only 7% of the households heated their homes to maintain higher temperatures during summer and most of the households tend to keep their heating system off during the summer period). The results of this study and the results of others thus support the statement of Lomas and Kane [12] that, "*whilst the BSEN15251 method has great promise conceptually for assessing comfort in free-running homes it isn't clear how it might be used in practice*". Further research is needed to develop a better method for assessing thermal comfort in existing homes.

4.3. Data uncertainty

The private world of occupied homes inevitably results in compromises between research ideas and what can be achieved in practice. In this study, it was not certain where the sensors had been placed and that they would not be exposed to heat sources (such as solar gain and electronic devices). In addition, there was only a single sensor in each space although spatial temperature variations will occur. Therefore, the temperatures that the sensors were measuring may not actually be representative of the whole space air temperature or the temperature felt by the occupants. It was also impossible to verify whether the bedrooms and living rooms were actually occupied during the assumed occupied hours. It is difficult to imagine how multiple sensors all of which are suitably shielded from radiant and conductive sources could be deployed in occupied homes. However, improved accuracy might be achieved in future in homes in which digital technology is used to control heating systems and where smart meters and gateways provide a channel from which to collect data from wireless temperature, occupancy and other sensors.

5. Conclusions

This study is believed to be one of the first large national scale assessments of summertime temperatures and thermal comfort in English homes. Some caution is however needed, when interpreting the findings. Firstly, considering the wide range of dwelling types and geographical areas covered, it seems that the sample of 207 dwellings may not be sufficiently large to fully capture the whole range of differences that exists within the English domestic stock. Secondly, the work is based on temperatures measured in living rooms and bedrooms between 22 July and 31 August 2007 and the summer of 2007 was surprisingly cool, which will depress internal temperatures in general and the occurrence of elevated temperatures in particular. Thirdly, some of the data appeared to be in error and 14 of the homes (7%) were deemed to be heated during the monitoring period. Although the method chosen for finding the erroneous data, and for identifying heated homes, had been adopted in a previous study [12], human judgement and a pragmatic approach was involved in the process.

Thermal comfort in the living rooms and bedrooms of the 193 free-running buildings that yielded error free data was assessed using both static criteria, based on CIBSE recommendations, which are designed to indicate elevated temperatures, and the BSEN15251 adaptive thermal comfort criteria. Despite the cool summer conditions, a large proportion of living rooms and bedrooms had more than 5% of their occupied hours above the CIBSE recommended temperature thresholds of 25 °C and 24 °C respectively. Moreover, a considerable number of bedrooms exceeded more than 1% of occupied hours above the 26 °C threshold. The incident of warm bedrooms is even more striking when considering only the post-1990 dwellings and flats; 80% and 74% of the bedrooms respectively, exceeded above the 5%/24 °C criterion with 55% and 32% respectively also exceeding the 1%/26 °C criterion. Considering different GORs, as expected, the warmer homes were found in London, the South East, the East, the East Midlands, and the West Midlands, whereas the cooler homes were in the North East, North West and Yorkshire. This incidence of elevated temperatures, found in one of the coolest English summers of the last decade, raises concerns about the potential risk to comfort and health that might arise in much warmer years especially in warmer regions of the England. The findings suggests that serious attention should be paid to adaptation of the modern dwellings (i.e. post-1990 and flats) to avert the risk of elevated temperatures especially as there is a strong trend towards even better insulation standards in new homes. Furthermore, refurbishment programmes, designed to reduce energy consumption in winter, should also ensure that indoor temperatures in summer are not exacerbated.

The findings of the thermal comfort assessment using both the static and BSEN15251 adaptive thermal comfort criteria were consistent with the observations made in previous studies [6,8,12,27–29], notably, that the oldest dwellings (pre-1919), solid wall houses and detached homes were significantly cooler than more modern homes, homes with cavity wall construction and homes of other built-form types. In the cooler homes, there were significantly more living rooms and/or bedrooms with more than 5% of their occupied hours below the BSEN15251 Cat II and/or Cat III lower thresholds. On the other hand, significantly fewer flats, and in particular top floor flats and post-1990 dwellings, were found to be below these thresholds. A number of potential reasons for these findings have been discussed (Section 4.1).

The results of the thermal comfort assessment aligned with those from the similar, city-scale study [12] indicated that many English households choose living room and bedroom temperatures below than those anticipated by the BSEN15251 standard. In this work, more than 50% of living rooms and bedrooms had more than 5% of occupied hours below the Cat III lower threshold (moderate expectations, applicable to existing buildings). Furthermore, the proportion of cool homes was greater in the cooler areas of the country, such as Yorkshire and the North East, than in the other, warmer areas. Since the adaptive standard accounts for differences in ambient temperature, this result suggests that the occupants of cooler regions are more tolerant of cool indoor temperatures than those living in warmer regions. This brings into question the reliability of the BSEN15251 standard for assessing thermal comfort in occupied homes and perhaps the need to tune the thresholds to reflect the differences in occupants' perception in different geographical regions. The matter was discussed more fully in Section 4.2.

The findings of this work, supported by further larger national-scale field measurement work, could be used to develop a framework for prioritising dwellings that should be adapted to withstand hotter summers, especially as the climate of England warms. However, more work still needs to be done to understand what temperatures are, and are not, acceptable in English homes in different regions.

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