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Dwelling and household characteristics' influence on reported and measured summertime overheating: A glimpse of a mild climate in the 2050's

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ABSTRACT

The summer 2018 saw temperatures far above the long-term average in the Northern Hemisphere. It was England's hottest ever summer, with temperatures typical of those expected of the 2050s. In the largest and most comprehensive study to date, summertime overheating in 750 English homes was assessed through both monitoring and questionnaires.

Overheating determined using adaptive thermal comfort criteria invariably produced patterns of overheating with dwelling and household characteristics comparable with self-reported results for both living rooms and bedrooms. However, households with members aged over 75 significantly under-reported the prevalence of overheating compared with monitored results. The standard UK static overheating criterion produced implausible estimates for the prevalence of overheating in bedrooms.

Weighting the results to the national stock revealed that 4.6million English bedrooms (19% of the stock) and 3.6million living rooms (15%) overheated. Overheating was more prevalent in bedrooms at night than in living rooms during the day. The prevalence of living room overheating was significantly greater in flats (30%) than other dwelling types. Improved fabric energy efficiency did not significantly increase the risk of overheating. The prevalence of monitored overheating was greater in households living in social housing, with low incomes or with members aged over state pension age.

Recommendations are made about the measurement of overheating and the formulation of policies aimed at mitigating the risk of overheating in existing homes.

1. Introduction

The threats posed by climate change are of world-wide concern. Global temperatures are likely to be c1.5 °C above pre-industrial levels by 2052 [1]; and heatwaves will increase in frequency, intensity, and duration [2]. High summertime temperatures are linked to excess mortality and morbidity [3] and the majority of fatal heat exposures in developed nations occur indoors [4]. The elderly and very young, those with chronic physical and/or mental health conditions, and the immobile and bed-ridden are especially vulnerable [5,6]. In England's hottest summer to date, 2018 [7], which is the focus of this research, there were four heat waves, resulting in 1067 excess deaths, with far more deaths being recorded in London than elsewhere in England [8].

Summertime overheating in homes has been identified in many temperate regions where domestic air-conditioning is rare, e.g., France and Germany [9], the northern USA [10], the UK and New Zealand [11]. In the UK, overheating occurs in homes across all regions [12], including Scotland [13] and is expected to increase [14]. High, but non-fatal temperatures can lead to thermal discomfort and have a detrimental impact on health and well-being [15], reduced productivity and increased accidents [16] thereby placing an increased burden on health services [17].

Computer modelling has been used since the early 1990's to assess the risk of overheating in buildings (e.g., [18,19]). Modellers had to devise criteria with which to determine if a room in a dwelling is, or is not, overheated. Initially these were static criteria [18,20] and, through

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custom and practice, these became incorporated into industry guidelines and standards in the UK (e.g., [21,22]), and elsewhere (e.g., [9,23]). For UK bedrooms, a 26 °C/1% criterion was adopted, i.e., the operative temperature in the bedroom should not exceed 26 °C for more than 1% of annual occupied hours. Static criteria, and the 26 °C/1% criterion in particular are, however, increasingly contested (e.g., [11,24,25]); a debate to which this paper contributes.

It is now accepted that daytime thermal comfort assessments should be based on adaptive criteria, e.g., BSEN15251 [26,27] and TM52 [28] in which the threshold of acceptable indoor temperature increases and decreases in line with the outdoor temperature.[1] The rate at which people adapt with outdoor temperature is based on thousands of field measurements of thermal comfort gathered from across the globe[2] (e.g., [29,30]). Overheating criteria based on the adaptive model have been devised and incorporated into guidelines and standards, e.g., Standard 55 [31] and TM59 [32]. In the UK, adaptive criteria are not used to assess overheating at night when people are asleep. Rather unexpectedly, this matter became important to the work reported here, and is discussed more fully below.

Field measurements provide the most compelling evidence of the extent and severity of overheating in different building types. Questionnaire surveys capture occupants' perception of overheating and are easier and faster to undertake than monitoring studies, but the reliability of the results is heavily dependent on the questions asked and when the survey is delivered. The reliability of such surveys becomes a matter of concern in this work.

Monitoring campaigns, in which small temperature sensors are installed in homes, provide the most objective and detailed assessment of the prevalence, severity and timing of overheating. Such studies have identified which existing occupied dwellings and, importantly, which households are most at risk of overheating. The large-scale surveys of [12,33] have been particularly influential in alerting UK policy makers to the problem of overheating [34–36]. In 1998 and 2011, the government supported the England-wide Energy Follow-up Surveys (EFUSs) [37]. The 2011 EFUS survey monitored temperatures in the cool summer of 2010 [38]. Analysis using the TM59 overheating criteria has reported overheating in the living rooms and main bedrooms in 2.5% of English homes [25]. The results of the 2011 EFUS are compared with the 2017 EFUS results in this paper.

Monitoring studies have begun to reveal patterns in the occurrence of overheating in UK housing stocks. There is clear evidence that flats (apartments) are more likely to overheat than other building types, some chronically so [39]; and dwellings within the London urban heat island might overheat more than those in cooler areas of the country [12]. Well-insulated homes are sometimes reported to have a higher risk of overheating than less energy efficient homes, and sometimes not [40]; occupant behaviour can play an important role [13]. The lack of clarity arises because different dwelling samples are used, the prevailing weather differs, and because of problems applying current overheating criteria (devised for modellers) to monitored data. The study reported here overcomes some of these problems.

This paper reports the methodology and results of the largest and most comprehensive study of overheating in English homes, the 2017 EFUS. Temperatures were monitored in the living rooms and main bedrooms of 750 homes across England, during 2018. This was England's hottest summer on record [7] but typical of those that will be experienced in the 2050's [41]; the results provide a glimpse into the future. The elevated temperatures generated widespread overheating enabling the statistical significance of dwelling and household characteristics to be identified more clearly than ever before. The monitored data is compared with households' self-reported prevalence of overheating, and overheating estimates based on different criteria are compared. The aims of this paper are three-fold: firstly, to bring clarity to the assessment of overheating based on measurement; secondly, to provide insight into which types of English dwellings and households are at risk of overheating and which are not; and thirdly, to help shape policies intended to mitigate overheating, and adverse health impacts, in existing dwellings.

2. Data collection and analysis

A brief description of the 2017 EFUS household, temperature monitoring and data analysis methods are given here; for a more complete description see [42,43]. Comparisons are made with the measurements made as part of the 2011 EFUS, the methodology and results of which have been previously reported [37,38].

2.1. The household sample and overheating measurement

The households recruited to the 2017 EFUS were sampled from those that participated in English Housing Surveys (EHSs) [44]. The core sample consisted of 4950 households drawn from the 2016/17 EHS. This was boosted by 1265 households surveyed in earlier EHSs which, at the time, had been modelled as being in fuel poverty. All households had expressed a willingness to be recontacted. The EFUS sample was therefore non-random and biased towards households living in the social sector and/or in fuel poverty. Weighting factors are used to account for this oversampling and for non-response bias (section 2.4). For all the households, the EHS provided information about the characteristics of the dwelling and household: the dwelling age, type and size, the mode of heating and the level of insulation and overall energy rating; and the household size, composition, health,[3] income and mode of home tenure. Householders in 10 homes in the living room sample and 8 in the bedroom sample reported having air conditioning units.

A pilot questionnaire was delivered between May and June 2017 (94 households) followed by the main questionnaire between August and January 2018.[4] Together these produced responses from 2,632 households, of which 2,538 responded to the questions about overheating. This asked about: the temperatures in the living room and main bedroom during the 2017 summer (which, in the UK, is defined as June to August inc.); the perceived causes of the high temperatures; and the steps taken to stay cool. The end-of-summer timing of the questionnaire was intended to ensure that households would have a reasonable recall of the thermal conditions in the previous summer.[5]

Just under half of the households that completed the questionnaire (1,020) consented to the temperature monitoring. Loggers, with an accuracy of ±0.4 °C [45] were placed in the living room and main bedroom and up to three other spaces, either by the trained EFUS surveyors or, if preferred, by the households themselves (typically for bedrooms). The loggers were deployed between August 2017 and October 2017 and recorded temperatures at half-hourly intervals until April 2019, thus covering the whole 2018 calendar year. The loggers from 750 households were suitable for analysis after the initial data cleaning.

Comparisons are made between the measurements made in 2018, the self-reported overheating in the summer of 2017, and the monitored

[1] Increasing and decreasing by 0.33 K per K change in the exponentially-weighted running mean of the daily mean outdoor temperature in BSEN15251.

[2] Which includes climates much warmer than the UK thus rendering the data applicable to the warmer UK temperatures that will be experienced in the future.

[3] Persons who reported suffering from long-term illness or disability.

[4] Face-to-face interviews were conducted with 1,867 households between August and October 2017 and, to boost the sample, a further 671 households completed on-line questionnaires between October and January 2018.

[5] In this paper, no attempt is made to examine the self-reports of overheating from the 2011 EFUS because the questionnaire was delivered in the middle of winter and asked different questions to the 2017 EFUS.

data from the 2011 EFUS. The 2011 survey measured temperatures at 20-min intervals in the living room and main bedroom during the summer of 2010. Previous temperature analysis has focussed on comparison of room temperature [25,38]. Here the 2011 EFUS data is reanalysed using contemporary overheating assessment methods and criteria.

2.2. The weather during the three summers

The summer of 2018 was exceptional, *" …. the joint hottest summer season (June, July, August) in the Met Office UK national temperature series"* [46]; *"and it was the warmest on record for England."* [7]. The daily mean, and daily mean maximum temperatures in May and July were amongst the hottest ever recorded (i.e. since 1884) and May was the second sunniest (Table 1). The highest temperature recorded was 35.3 °C in Faversham (Kent) on the July 26.[6] This hot spell was followed by a thunderstorm, with temperatures dropping sharply on July 28th. The latest set of UK climate projections (UKCP18) estimate that a 2018-like summer could be more common than not by the mid-twenty-first century. Detailed analyses by the UK Meteorological Office [7] conclude that, "*the latest set of UK climate projections (UKCP18) estimate that a 2018-like summer could be more common than not by the mid-twenty-first century*", which leads [41] to note that "*these summer temperatures could be normal by the 2050s*." The summer of 2017, after which the self-reports of overheating were solicited, was also warm, the 18th hottest since 1884 based on the mean temperature [47]. June was especially warm, the hottest for over 40 years, and the second hottest on record (Table 1). August was relatively cool by current standards, which may influence the self-reporting of overheating. There were two heatwaves, on 16th June and 5th July which lasted for eight and two days, respectively[7] [48].

The summer of 2010, when the 2011 EFUS monitoring was undertaken, was cooler than the other two years, with August being especially cool and close to the long-term average (Table 1).

2.3. Cleaning the monitored data

The measured half-hourly values from the living room and main bedroom for the period from May to September[8] were plotted and inspected by eye. Room data was removed from the sample if: there was no recorded data; there were curious temperature spikes suggesting solar radiation incident on the sensor or other heat source effects producing implausible readings; loggers were recording very similar temperatures, suggesting the sensors had been placed in the same location; there were distinct changes in the temperature trace, suggesting, perhaps, that the sensors had been moved; or if there were other 'strange', thermally inexplicable, data anomalies. Altogether the data cleaning process removed 134 living rooms and 159 bedrooms from the sample leaving a total of 616 living rooms and 591 bedrooms for the overheating analysis. The data from the 2011 EFUS was cleaned and organised following the same process, yielding reliable temperatures for 749 living rooms and bedrooms.

In the 2017 EFUS dataset, both living room and main bedroom temperatures were available from 517 homes, of which 285 (55%) displayed evidence of space heating at some time during the five-month period.[9] Such heating was usually for brief periods in the evening in the living room or the bedroom. In the analysis undertaken, no distinction was made between heated and unheated homes.[10]

Previous monitoring studies have adopted a similar data cleaning approach, reported similar anomalies in the measurements and also observed summertime space heating [12,33].

2.4. Weighting to the national stock

The weighting method is fully described elsewhere [42] but, in brief, each home in the questionnaire sample was weighted to represent all similar homes in the English housing stock (23.95 million in 2017) using a Random Iterative Method (RIM) and logistic regression based on the dwelling type, location and characteristics of the household. An additional weighting factor was derived for the subset of households with valid temperature data (total English households in 2018, 24.17 million). After weighting, each home in the 2017 EFUS represented between 4,000 and 225,000 other English homes. Similar weighting processes had been adopted for the temperatures recorded in the 2011 EFUS (total households in 2010, 21.9 million). Throughout this paper, the reported percentages of overheated homes always relate to the English stock as a whole for the relevant year rather than the percentage of the monitored sample.

2.5. Analysis of self-reported overheating

Following much discussion[11] and trials with households, the term '*uncomfortably warm*' was adopted to describe a thermal sensation associated with indoor conditions indicative of overheating. Therefore, in the questionnaire delivered after the summer of 2017 [42], the occurrence of warm conditions in the main rooms was obtained from responses to the question:

"*In a typical summer (June to August), how often does the main bedroom/living room feel uncomfortably warm?*"

The same question was asked about each of the rooms with six possible responses offered: 1. Never, 2. Rarely, 3. Sometimes, 4. Often, 5. All the time, 6. Don't know. In interpreting the questionnaire responses '*rarely*' and '*sometimes*' were deemed to represent an acceptable frequency of warm temperatures, but '*often*' or '*all the time*' were not; so rooms that were uncomfortably warm often or all the time were classed as overheating. It was assumed that the living room responses referred to the daytime and the bedroom temperatures the night-time.

In the 2011 EFUS, households were asked if they experienced difficulty keeping rooms cool between June and August in a typical summer [38]. The questionnaire was delivered a long time after the preceding summer and the form of this question, which relates to the (practical difficulty of) cooling rooms in an (imagined) 'typical' summer, precluded comparisons with the 2017 EFUS questionnaire responses.

2.6. Analysis of monitored temperatures

The daytime temperatures monitored in the living room were assessed using criteria founded on the adaptive thermal comfort approach. The night-time temperatures in the main bedroom were assessed using the established static 26 °C/1% criterion and, for reasons explained below, adaptive thermal comfort criteria.

As noted above, overheating criteria are framed by the requirements

[6] The highest ever temperature in England, 38.7 °C, was recorded in Cambridge on 25 July 2019 [41].

[7] These caused 888 excess deaths, more in the SE than the other English regions.

[8] The period over which overheating is assessed by the adaptive criterion in TM52.

[9] Space heating was characterised by sharp temperature rises, which could not be explained by solar gains, and which reoccurred at a similar time each day when occupants would probably be present in the room.

[10] Analysis showed that the prevalence of overheating in the heated and unheated rooms was very similar, but slightly less in the heated rooms.

[11] Including consideration of using the established ASHRAE and Bedford scales with a Likert rating approach.

Table 1
Mean monthly and mean daily maximum temperatures and rankings since 1884 and 2000, for three English summers.

	Summer 2010			Summer Overall	Summer 2017			Summer Overall	Summer 2018					Summer Overall
	June	July	Aug.		June	July	Aug.		May	June	July	Aug.	Sep	
Monthly mean														
Temperature/°C	15.0	17.1	15.3	15.69	15.9	16.5	15.6	15.98	12.9	15.8	18.8	16.7	13.6	17.10
Rank 2000>	7	7	19	12	1	10	17	8	2	2	2	8	16	1
Rank 1884>	14	19	74	26	2	33	57	18	2	4	2	24	55	1
Mean daily maximum														
Temperature/°C	20.3	21.6	19.6	20.49	20.3	20.9	20.0	20.40	18.4	21.1	24.8	21.3	18.1	22.40
Rank since 2000	4	7	20	8	5	10	17	11	1	3	2	6	12	1
Rank since 1884	15	30	80	29	16	45	64	34	1	3	2	30	47	2

Rankings are since 2000 inc. and for the entire English temperature record, i.e., since 1884 inc., as listed to Jan 01, 2021 by the Met Office [48]. Precision quoted is that provided in the source.
Data are shown only for the months relevant to the overheating analyses, the three summers June to August and the longer period, from May to September, for 2018.

of modellers, and whilst BSEN15251, TM52 and CIBSE Guide A suggest they can be used in monitoring studies, advice on how to do this is far from comprehensive and in some areas inconsistent[12] (see also [11]). An effort is therefore made to describe as clearly as possible the approach used here so that others might, beneficially, adopt a similar approach in future studies.

The static overheating criterion was taken directly from TM59:

"*to guarantee comfort during the sleeping hours the operative temperature in the bedroom from 10 p.m. to 7 a.m. shall not exceed 26 °C for more than 1% of annual hours.*"

To apply the criterion, each half hourly bedroom temperature recorded between 22:30 and 07:00 on each day between 00:30 on January 01 and 24:00 on December 31, 2018 was compared with the 26 °C threshold and the total divided by two to get the total annual hours of overheating (He). If He was 33 h or more (i.e., more than 1% of the annual occupied hours) then the bedroom was deemed to be overheated. The temperatures recorded by the loggers were used throughout as a surrogate for the operative temperature[13] but they may actually be rather closer to operative than air temperature (see e.g., [11]).

Adaptive thermal comfort analysis recognises that people adapt to warmer temperatures, both psychologically and physiologically, and that this adaptation depends on the previous temperatures that people have experienced. The adaptive temperature threshold, T_{max},[14] above which spaces are considered to be too warm, increases with the exponential running mean of the mean daily outdoor temperature, T_{rm}, [28]. Different thresholds have been established which depend on peoples' thermal expectations (Fig. 1), being 1 K lower for very sensitive and fragile persons (Category I), compared to people with a normal expectation (Cat.II), and 1 K higher than Cat.II for those with a moderate expectation (Cat.III).

The adaptive overheating criteria are based on the positive difference, ΔT, between the room's measured operative temperature at a given time, T_o, and the relevant threshold (T_{max}). Various criteria have been established which define the frequency and degree of exceedance of these thresholds that constitutes overheating. In this work the first of the three criteria defined in TM52 was used, which is also the criterion

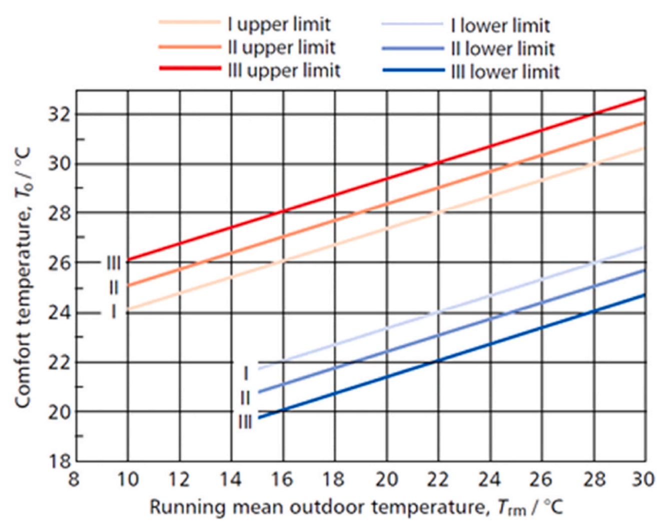

Fig. 1. Adaptive thermal comfort thresholds, for sensitive and fragile people (Cat.I) persons with normal expectations (Cat.II) and persons with moderate expectations (Cat.III), source [28].

adopted in TM59 for both living rooms and bedrooms[15,16]:

"*The number of hours (He) during which ΔT is greater than or equal to one degree (K) during the period May to September inclusive shall not be more than 3 per cent of occupied hours*"[17,18].

Interestingly, TM52 states that '*ΔT is rounded to the nearest whole degree (i.e., for ΔT between 0.5 and 1.5 the value used is 1 K; for 1.5 to 2.5 the value used is 2 K, and so on)*'; although no reason for doing this is given.[19] Because of this rounding, any ΔT more than 0.5 K above the thresholds in Fig. 1 rather than 1 K, as the criterion says, fails the criterion. This convention was adopted in this work.

The rooms were assumed to be occupied for the same periods on weekdays and weekends. Bedrooms were taken to be occupied for 9 h, i.

[12] CIBSE Guide A (2015) says for example that '*The measurement period for all measured parameters should be long enough to be representative, for example 10 days*' and '*under representative weather conditions*'.

[13] The indoor operative temperature most closely relates to people's temperature perception. At the low air velocities that prevail in homes, it is the average of the air and mean radiant temperature.

[14] Called *'the limiting maximum acceptable temperature'* in TM52 [28].

[15] But unlike in this study, TM59 prescribes that bedrooms are occupied for 24 h each day.

[16] TM59 states that the first criterion must be met even though '*Criteria 2 and 3 of CIBSE TM52 may [also] fail to be met …*'. Out of interest, in this study, very few living rooms failed the third criterion in TM52 and the numbers failing the second criterion were similar to those failing the first.

[17] The criterion continues with, '*If data are not available for the whole period (or if occupancy is only for a part of the period) then 3 per cent of available hours should be used',* but this is not relevant to the work reported here.

[18] BSEN15251, also quotes a maximum allowable value of 3% of occupied hours.

[19] Enquiries of the author of TM52 indicated that the rounding was associated with considerations around the precision of temperature measurements.

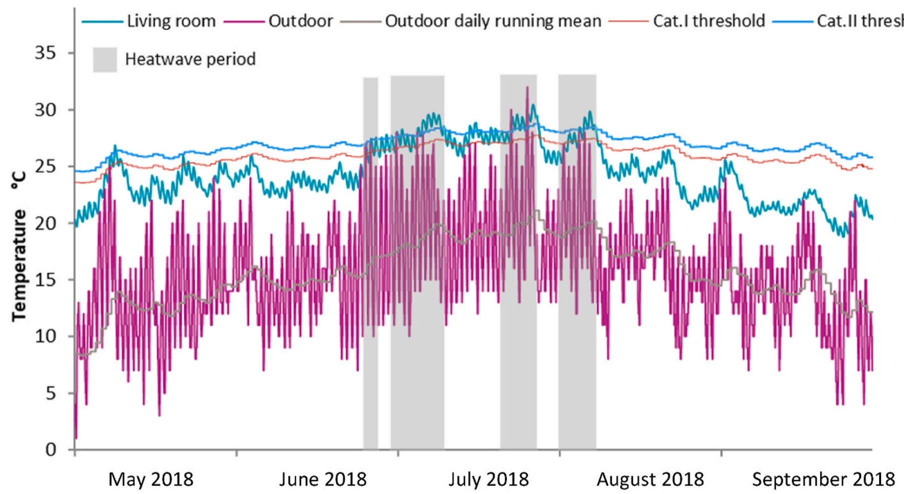

Fig. 2. Temperatures between May and September in a 'hot' living room showing: the outdoor temperature; the four heat waves; the daily running mean of the outdoor temperature (T_{rm}); the adaptive thermal comfort thresholds for Cat.I and Cat.II households; and the measured half-hourly living room temperatures.

e., the half hours from 22:30 to 07:00, which is the same period as used with the 26 °C/1% static criterion. Thus, 3% of occupied hours between May and September (153 days), gives a threshold for *He* of 41.5 h. The occupied hours for the living rooms were taken as 07:00 to 22:00 inc.,[20] thus the half hourly temperatures from 07:30 to 22:00[21] were used to assess whether the living room overheated. The living room is thus occupied for 15 h a day which gives a limiting value for *He* of 69 h.

In reality of course, neither the living room nor the bedroom is likely to be occupied at the defined times every day for 5 months. In monitoring studies therefore, the 'occupied hours' are, in effect, a convention, albeit a reasonable one, adopted for analysis purposes; the same, or a similar convention to that proposed here has been adopted in other monitoring studies (e.g., [12,33,49,50]).

The adaptive thermal comfort analyses was undertaken using the Cat.II threshold for all homes and also, as suggested by TM59, by selecting the category, either Cat.I or Cat.II, depending on the heat-sensitivity of the household. Using the same criterion for all homes (Cat.II) enabled a like-for-like comparison of the inherent tendency of homes to overheat given each dwelling's physical characteristics and the way it was used by the occupants. The selected category (Sel.Cat.) approach provides a more credible estimate of the impact of heat on English households. When heat-sensitivity is accounted for, the prevalence of overheating (for different dwelling and household characteristics) is always higher than when heat-sensitivity is not accounted for (Cat.II).

There is no established convention for defining heat-sensitive households, so in this work households were classified as heat-sensitive (Cat.I) using the *EFUS-vuln* variable derived from the questionnaire, i.e., households with members who were either aged 75 or over, or under 5, or had long-term sickness or were registered disabled. In both the living room and bedroom samples, 53% of households were classed as heat-sensitive. The assignment of heat-sensitivity to a household and not to individuals, as the theory behind adaptive thermal comfort intends, is worth noting.

The Sel.Cat. approach permits credible comparisons with the prevalence of overheating reported by households. However, in the 2017 EFUS, the self-reports were concerned with the summer period (June to August), therefore, the prevalence of overheating was re-calculated, by applying the adaptive criterion only for the half-hourly temperatures recorded during the summer. This also enabled an examination of the effect of the monitoring period on the calculated prevalence of overheating.

The running mean of the daily outdoor temperature (T_{rm}) is needed to apply the adaptive criterion. Therefore, each home was matched with its nearest British Atmospheric Data Centre (BADC) weather station [51]. Around 150 weather stations were used, with each station paired, on average, with five dwellings. The T_{rm} was calculated following the TM52 procedure using an alpha value of 0.8 used in the T_{rm} calculation.

The outside air temperatures recorded close to one of the monitored homes and the four heat wave periods, all between June 25 and August 09, lasting between three and 11 days, are illustrated in Fig. 2. Across all the monitored homes in the 2017 EFUS, the highest recorded outdoor temperature was 34.4 °C on July 26 near a dwelling in Surrey. The daily running mean of the outdoor temperature (T_{rm}), and the Cat.I and Cat.II thresholds (T_{max}) are also illustrated in Fig. 2. The maximum value of T_{rm} for the 2017 EFUS sample was 24.6 °C,[22] which was recorded in London. Note how T_{rm} lags the outdoor temperature by a day or so, and likewise how, in this dwelling, the peaks in living room temperature lag the outdoor temperatures, possibly due to the thermal inertia associated with the thermal mass of the dwelling.

2.7. Identifying patterns of overheating

To identify which dwellings may have a higher or lower prevalence of overheating, the dwellings were divided into different categories (house type, energy efficiency rating, etc) and then, within each category, by their characteristics (semi-detached, detached, flat, etc). The same approach was also adopted to identify patterns of overheating with household characteristics.

Patterns in the prevalence of overheating with characteristic were then identified for both the bedrooms and living rooms based on the nationally-weighted percentage that overheat (as determined by the TM52, Sel.Cat. approach with data from May to September). Chi-squared tests were then used to identify if there is a significant different in the prevalence of overheating depending on the characteristics. Alongside this, the Z-test for proportions was used to determine where the differences occur, with a Bonferroni correction. Sometimes, to clarify where statistical differences exist, characteristics are grouped together (eg. overheating in flats is compared with that in all other house types).

[20] Thus, the two occupied periods cover the 24 h of each day.

[21] All timings were British Summer time (Greenwich Meantime plus 1 h).

[22] Which corresponds to adaptive threshold temperatures of approximately 29 °C and 30 °C for Cat.I and Cat.II people respectively (Fig. 1).

In reporting the results and illustrating the patterns of overheating (Section 3.3), only statistically significant results at the 99% level (where $p < 0.01$) are discussed, although some instances when results that are significant at the 95% level ($p < 0.05$) are reported. Appendix A contains the analysis tables. Occasionally, where relevant, the significance of results using the Cat.II approach are also stated. These analyses are also in the Supplementary Information to this paper [52].

To test the robustness of the results, the analyses were repeated using the TM52 approach but with the measured data from the summer period (June to August) only. This enabled direct comparison with the 2011 EFUS results, which had been generated for this period, and with the self-reported data, which also related to the summer period. For these analyses see the supplementary information to this paper [52]. Importantly, the household and dwelling characteristics for which there were significant differences in the prevalence of overheating were remarkably similar to those found using the longer data period (May to September).[23] This is reassuring and gives confidence that the observed patterns are real and not an artifact of the data period chosen. This observation also suggests that overheating analyses might be based on monitoring over shorter time periods and yet still provide valid insights about which dwellings and households are most affected by overheating.

For the categories in which a significant difference in the prevalence of overheating depending on the characteristic had been identified (TM52, Sel.Cat, May to September approach) bar charts are used to show the patterns of overheating (Section 3.3). These compare the self-reported and monitored prevalence of overheating for the summer period, June to August. Observations are made concerning the significance of the self-reported prevalence of overheating (see the supplementary information [52] for these analyses). As will be seen, there is remarkable consistency in the patterns of measured and reported overheating although the absolute values differ systematically.

3. Results

Firstly, the effects on results of using a different overheating assessment period, different criteria and different overheating thresholds is illustrated. Secondly, the headline results for the prevalence of overheating in the English dwelling stock are presented for 2018, as reported for the summer of 2017 and as measured in 2010. Finally, bar charts are used to illustrate the patterns of summertime overheating.

3.1. Effect of overheating assessment methods

The most obvious difference in the estimated prevalence of overheating in the English housing stock is the much higher prevalence of overheating in bedrooms indicated by the static 26 °C/1% overheating criterion (69%) (Fig. 3). This is more than three times greater than the prevalence produced by the adaptive criteria, and four times greater than the prevalence of reported overheating. The analysis of the 2010 data yielded almost a ten-fold difference, just 1.4% of bedrooms overheated using the adaptive criteria (Fig. 3) but 12.3% using the static criterion (not shown in Fig. 3).

Given the extraordinarily high, and implausible, prevalence of overheating produced by the static criterion, all further analysis of bedroom temperatures was conducted using the same adaptive criteria as for the living room. The implications of these results and the decision to use an adaptive approach for bedrooms are discussed more fully below (Section 4).

Focusing on the bedroom results produced by the adaptive criteria for 2018 (Fig. 3), it can be seen that the prevalence of overheating is approximately doubled if the Sel.Cat. rather than a Cat.II analysis is used (Fig. 3). This might be expected as the overheating threshold for the 53% of heat-sensitive[24] English households (Cat.I) is 1 K lower than for Cat.II (Fig. 1).[25]

For both the Cat.II and Sel.Cat. analysis, more bedrooms exceed the 3% criterion using temperatures monitored only during the summer (June to August), rather than over the longer period, May to September (Fig. 3). This is perhaps not surprising, as there tends to be a higher proportion of hot days in summer: although the higher outdoor temperatures are partly compensated for by the higher adaptive comfort thresholds (Figs. 1 and 2).

Similar observations about the prevalence of overheating in English living rooms depending on the method of 'measurement': the reported prevalence of summertime overheating in 2017 was about 2/3rds of that measured in 2018 (11% cf. 17%); the Cat.II analysis produced values that were about half those obtained using the Sel.Cat. approach; and the percentage of overheating living rooms was greater if temperatures from the summer period only were used for the analysis (Fig. 4).

Based on these results, for both the bedrooms and living rooms, the absolute values for the prevalence of overheating in 2018 (i.e., the percentage of the stock that overheats) is based on the measurements made between May and September in 2018 using the Sel. Cat. approach.

3.2. Overheating in English homes, headline results

During 2018, in England as a whole, 3.6 million homes (15% of the stock) had living rooms that overheated and 4.6 million (19%) had overheated bedrooms. In the summer of 2017, 2.5 million living rooms (11%) and 3.8 million bedrooms (17%) were reported as overheated (Figs. 3 and 4).

The differences between the 2018 monitored prevalence and the 2017 reported prevalence is to be expected given that the summer of 2017 was cooler than the summer of 2018 (Section 2.2). However, there may be other reasons for such differences, on one hand the quality of the temperature data and the criteria used to analyse them, on the other, the timing of the questionnaire and the reliability of self-reporting - a matter discussed more fully below (Sections 3.3.4 and 4.1).

In 2010, which was a much cooler year (Table 1), the monitored prevalence of overheating was substantially lower than in 2018; during the summer 0.6 million living rooms (2.1%) and 0.3 million bedrooms (1.4%) overheated[26] (Figs. 3 and 4). Given the small sample of overheated rooms, no attempt is made below to discern patterns of overheating by dwelling and household characteristics using the 2010 data.

The percentage of English bedrooms deemed to overheat was always more than the percentage of overheated living rooms. This result is observed irrespective of: whether self-reported or monitored overheating is considered; whether or not the monitored results accounted for the heat-sensitivity of the household; whether the analysis is for the summer period or for May to September; or whether the year of monitoring or reporting is 2010, 2017 or 2018 (compare Figs. 3 and 4). The fact that bedrooms overheat more at night than living rooms do during the day, even though outdoor temperatures are lower at night (when the bedrooms were deemed to be occupied) is an important finding from this research and is discussed further below.

[23] There were two instances where level of significance (1% or 5%) changed with monitoring period and two instances where there was a 5% significance for one monitoring period but not for the other.

[24] As defined in this work.

[25] Had all homes been assumed to be in Cat.I instead of Cat II, rather than 9% of living rooms being deemed to overheat during the summer the percentage would leap to 22%, the Sel.Cat. value was 17% (Fig. 3).

[26] Overheating in 2.5% of living rooms and bedrooms using the TM59 adaptive criterion and the Cat.II threshold was reported in [55]. The results were for the sample and not weighted to the English stock. They assumed the bedrooms to be occupied for 24 h a day as required by TM59 and living rooms from 09:00 to 22:00.

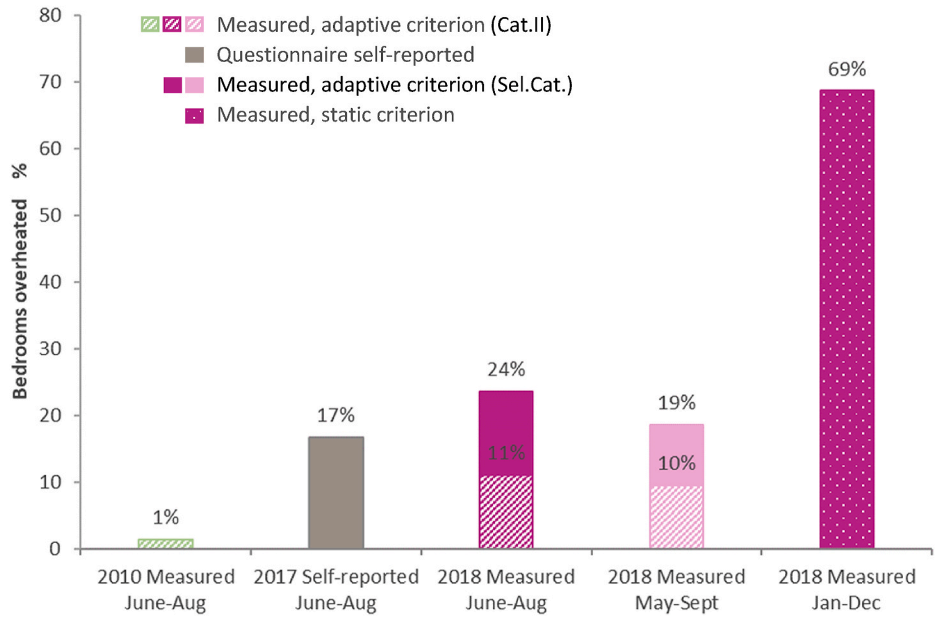

Fig. 3. Comparison of prevalence of overheating in English bedrooms as reported by households and as monitored in different years, over different time periods, assuming different heat-sensitivity, and using different overheating criteria.

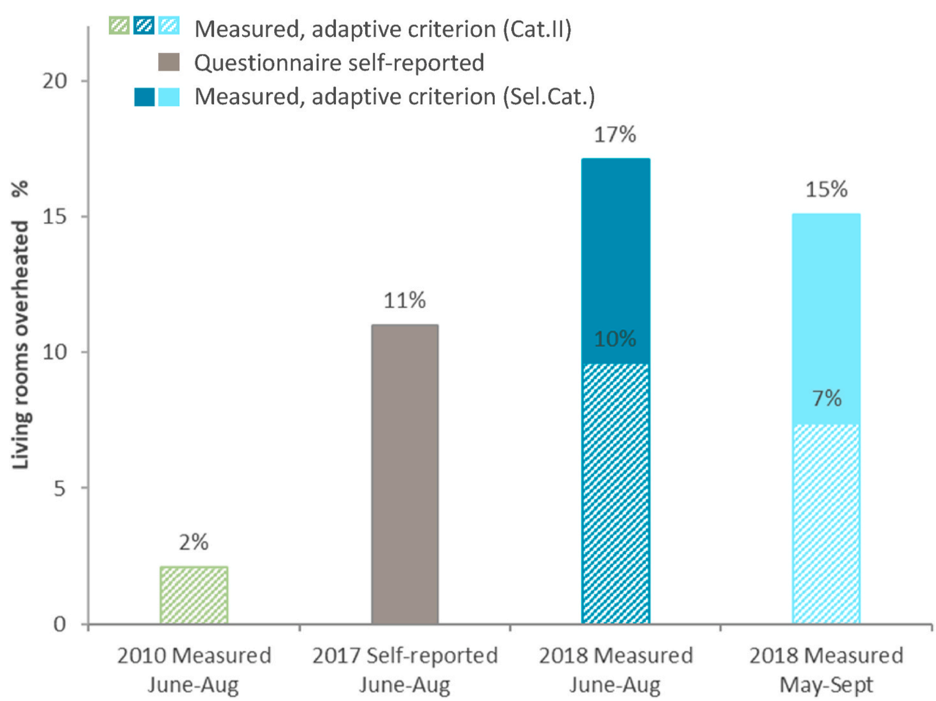

Fig. 4. Comparison of prevalence of overheating in English living rooms as reported by households and as monitored in different years, over different time periods, and assuming different heat-sensitivity.

3.3. Patterns of overheating

The patterns of overheating within different household and dwelling categories (e.g., house type) are examined in this section. For each category in which the household or dwelling characteristics have a significant impact on the prevalence of overheating, using the May to September data and the Sel.Cat. approach, bar charts are presented which compare the measured and self-reported patterns of overheating during the summer.

3.3.1. Comparison of living rooms and bedroom overheating

The headline results indicate that bedrooms are more prone to overheating than living rooms, even though the bedroom analysis is for the night-time period when outdoor temperatures are lower. This tendency prevailed across all the dwelling and household characteristics [52]. There were however instances where the reverse was true (i.e., more living rooms than bedrooms were overheated) but this reverse tendency was always associated with a characteristic that is typical of flats and other single storey dwellings. Specifically, living rooms overheated more than bedrooms in flats and bungalows, dwellings under 50 m^2 and with electric and non-central heating, and dwellings which had a good energy efficiency rating.[27] For example, the bedrooms of flats and dwellings under 50 m^2 overheated 17% and 20% of the time whereas the corresponding prevalence for the living rooms of such dwellings was 30% and 35%. The same trait was observed for single person households, which may also encompass a higher proportion of people who live in flats.

3.3.2. Influence of dwelling characteristics

Overall, there were significant differences in the prevalence of monitored overheating in living rooms depending on the dwelling characteristics ($p < 0.01$) but not the bedrooms[28] (Appendices A1 and A2). This suggests that living room temperatures are more heavily influenced by location and dwelling design than bedroom temperatures.[29]

Detached and semi-detached dwellings had the lowest prevalence of overheating, 10%, significantly lower than the prevalence of overheating in flats 30% (Appendix A1). The prevalence of monitored summertime overheating in the living rooms of flats was roughly double that in all other dwelling types (Fig. 5). The same difference was observed for self-reported results. The Cat.II results which indicate that the prevalence of overheating in flats is more than three times that in other dwelling types, suggests that it is the inherent design of the flats that is the primary cause of systematic differences in the prevalence of overheating (Fig. 5).

A clear pattern of increasing overheating as the dwelling size decreases was revealed by all methods of analysis, self-reported and monitored, Sel.Cat and Cat.II (Fig. 6). In the largest dwellings, those over 110 m^2, living room overheating only occurred in dwellings occupied by heat-sensitive households. The prevalence of overheating in the living rooms of dwellings under 50 m^2 (35%) was significantly greater, up to four times greater, than in larger dwellings, (e.g., 7% in dwellings over 110 m^2) (Appendix A1); the same significant result was obtained from the self-reports of overheating.

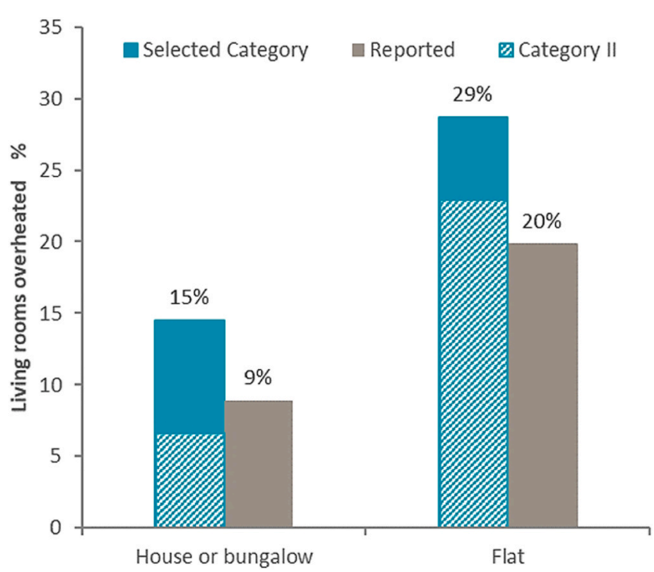

Fig. 5. Monitored and self-reported prevalence of summertime overheating in living rooms by dwelling type.

The monitored prevalence of overheating in the living rooms of London dwellings (28%) was greater than in each of the other English regions (e.g., 10% in the North West). Comparing the prevalence of overheating in London with that in the other eight regions combined (13%) revealed a significant difference using the Sel. Cat. approach (Appendix A1) and when using the Cat.II approaches or as self-reported [52]. The Sel.Cat. and Cat.II analysis revealed that bedrooms overheated significantly more in London (32%) than in other regions (17%) but only at the 5% level (Appendix A2). The self-reports of bedroom overheating were not significantly different.

There were no significant differences in the measured prevalence of overheating in either the living rooms or the bedrooms for any of the energy efficiency related measures (wall insulation, glazing type (either single or double glazing), depth of loft insulation, or the number of energy efficiency measures applied). However, households living in dwellings with the least loft insulation (<50 mm) were significantly more likely to report overheating in the living room than those households living in dwellings with greater levels of loft insulation [52].

Monitoring showed that the living rooms in homes with an energy efficiency rating band, as calculated by the UK Standard Assessment Procedure (SAP) [53] of A to C experienced more overheating (21%) than the living rooms of homes with a rating band of D to G (13%), this was only significant at the 5% level (Appendix A1). Likewise, the reported overheating in living rooms in homes with a rating band of A to C was significantly more (15%) than in less energy efficient homes (9%) [52]. However, these differences may be due to factors that influence the SAP rating other than fabric energy efficiency. The reasons for these results and their broader implications are discussed further below (Section 4.2).

3.3.3. Influence of household characteristics

There were clear patterns in the prevalence of overheating with the characteristics of the household for both living rooms and bedrooms (Appendices A3 and A4). For both rooms, overheating decreased as the income of households increased both as monitored and as reported (Fig. 7). Households in the two lowest income quintiles experienced a significantly higher prevalence of monitored and self-reported overheating in both rooms, than households in the three highest income brackets[30] (e.g., Appendix A3 and A4).

The monitored pattern of overheating was much less clear when the Cat.II approach was used for all households, which suggests that the overheating patterns were shaped primarily by the differing heat-sensitivities of poorer and more affluent households, rather than being an inherent feature of the dwellings in which they lived.

Whether families live in privately-owned homes (owner occupied or private rented) or in social housing (local authority or Registered Social Landlord, RSL)) has a clear impact on the prevalence of overheating (e.g., Fig. 8). The monitored prevalence of overheating in social sector homes was significantly greater than in homes in the private sector for both the bedrooms and living rooms[31] (Appendices A3 and A4). The differences for both rooms were also significant when the Cat.II approach was used for all dwellings and as reported by the households [52]. These results suggest the overheating was as much to do with the inherent tendency of social housing to overheat more than private housing as it was to do with the heat-sensitivity of the occupants.

Household size and composition also had an impact on the prevalence of overheating. The prevalence of overheating in bedrooms, both as reported and as monitored, increased with the number of occupants (Fig. 9), and was significantly less when households had either one member or two members rather than three or more members (e.g.,

[27] Energy rating A, B or C, as calculated using the UK Standard Assessment procedure (SAP) 2012 version [53]. Flats tend to have better energy efficiency ratings because they have fewer exposed walls.

[28] Although monitored bedroom results for region of the country were significant at the 5% level (Appendix A2).

[29] Occupancy characteristics may have an effect on the absolute prevalence of overheating in living rooms but not a systematic and significant effect.

[30] Significant at the 5% level as monitored in the bedrooms.

[31] Bedroom monitored results were significant at the 5% level.

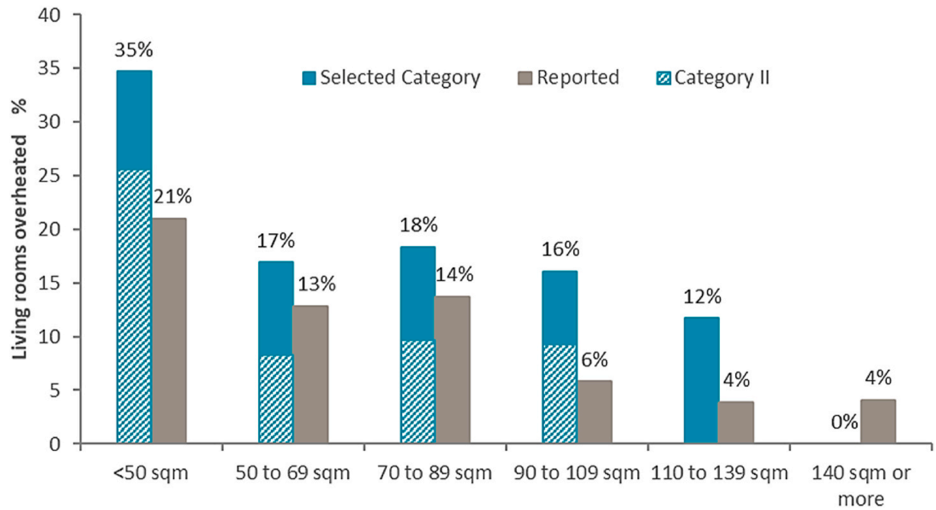

Fig. 6. Monitored and self-reported prevalence of summertime overheating in living rooms by dwelling floor area.

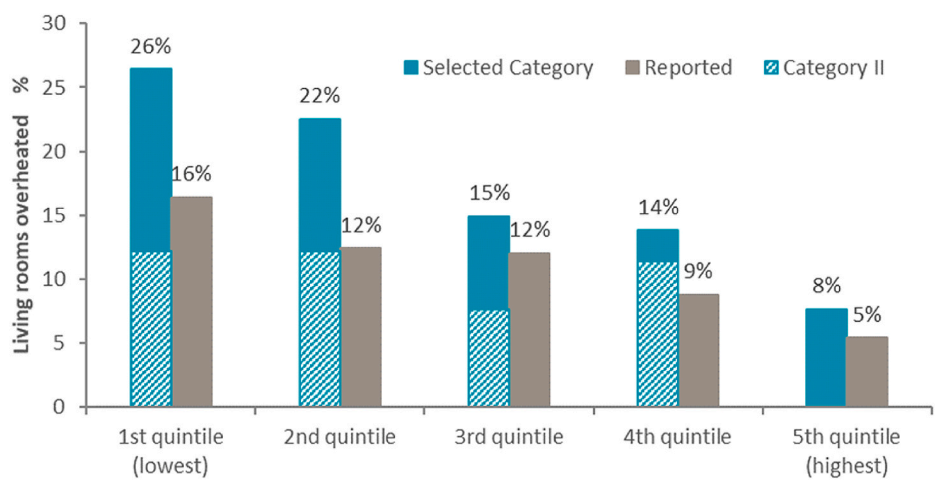

Fig. 7. Monitored and self-reported prevalence of summertime overheating in living rooms by income quintiles.

Appendix A4). No pattern was seen in the Cat.II results suggesting that the overheating in bedrooms is mainly due to larger households having heat-sensitive individuals than because the larger number of people induces overheating [52]. No such patterns were observed in either the monitored or reported living room results.

The prevalence of reported and monitored overheating was greater in both rooms for households with one or more children than in households with no children (Fig. 9). This seems to be primarily because households with children contain more heat-sensitive individuals rather than because of an inherent tendency for homes with children to overheat more (Cat.II). The self-reported differences were significant for both rooms[32] [52] but the monitored values were only significantly different for the bedrooms (Appendix A4).

3.3.4. Influence of age on reported overheating

Perhaps the most important observation, and one that has major implications for the conduct of overheating trials, is the stark difference between the patterns of monitored and self-reported overheating in both the living rooms and bedrooms in homes occupied by older people. There was a clear trend for the monitored prevalence of overheating in both rooms to increase with the age of the Household Representative Person (HRP)[33] (Fig. 10). Overheating was monitored in one third of living rooms where the HRP was over 75, this was a *significantly greater* prevalence than in homes where the HRP was under 65 (Appendix A3). The monitored prevalence was also significantly greater when the Cat.II approach was used, but only at the 5% level [52], which suggests that the type of dwelling occupied by the elderly has an impact but that their age and heat-sensitivity is the primary factor.

The monitored prevalence of overheating was also *significantly greater* in the living rooms of households that had persons of over state pension age than in households that did not (Appendix A3). And likewise, monitored overheating in living rooms was greater in households with persons that had long term illnesses or disability, or where there were no members in employment. Both are characteristics of households with elderly members. There was no significant difference in the prevalence of overheating in bedrooms with the age of the HRP or whether there were pensioners or ill and disabled members in the household.

In sharp contrast to the monitored results, the reported prevalence of overheating in both rooms decreased with the age of the HRP [52]; being just 8% in both living rooms and bedrooms where the HRP was

[32] But at the 5% level for the living room self-reported results.

[33] The HRP is the person in whose name the dwelling is owned or rented or who is otherwise responsible for the accommodation. This is not necessarily the same person that responded to the questionnaire.

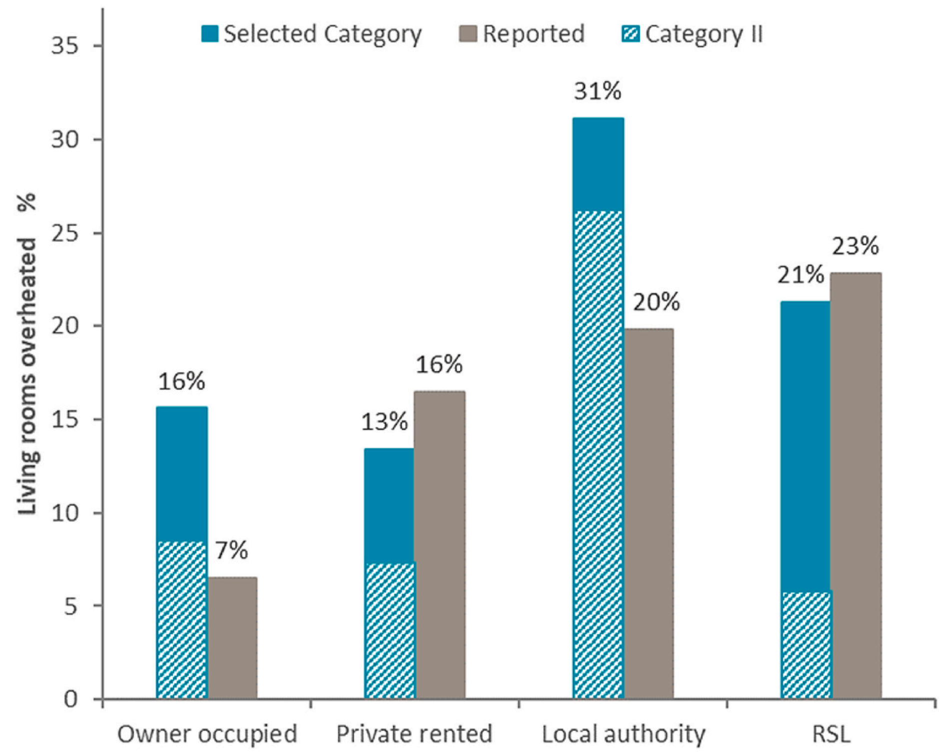

Fig. 8. Monitored and self-reported prevalence of summertime overheating in living rooms by tenure.

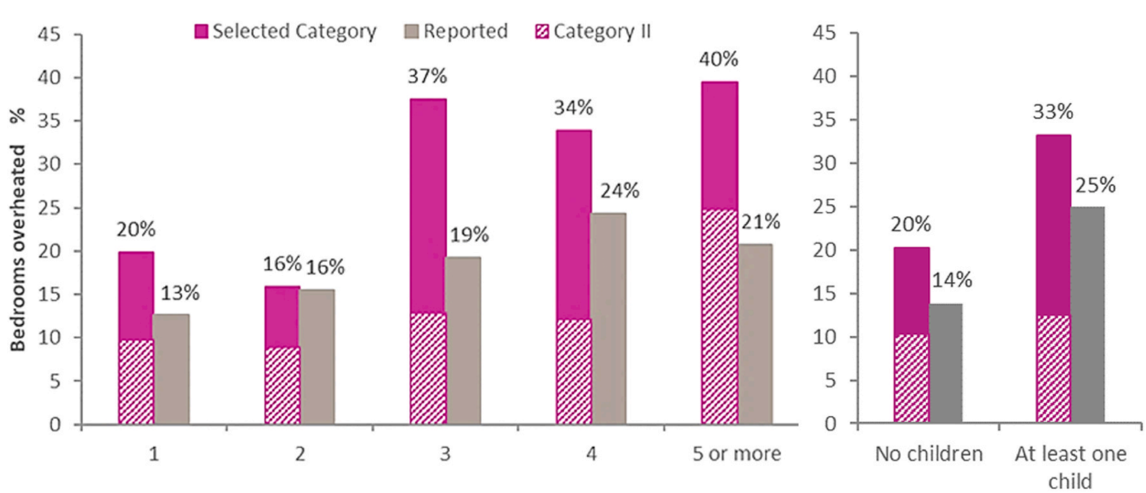

Fig. 9. Monitored and self-reported prevalence of summertime overheating in main bedrooms by household size and children present.

over 75, compared to 33% and 34% respectively, as determined from summertime monitoring (Fig. 10). In the bedrooms, the prevalence of reported overheating was *significantly lower* when the HRP was over 75 than under 65[34] [52]. Similarly, in both rooms, the prevalence of reported overheating, was *significantly lower* in households with persons over state pension age than in households where all members were under the pension age.[35] The differences between the monitored and reported patterns of overheating in the homes of the elderly, and the implications for overheating assessment, are discussed below.

[34] But only significant at the 5% level for the living rooms.

[35] There was no significant difference in the reporting of overheating in either room depending on whether household members suffered long term illness or disability.

4. Discussion

This section reflects on the overheating results and in particular: the influence of the method of measurement (self-reporting or monitoring), the choice of overheating criterion, the implications of the results for policy and practice, and the conduct of future field studies of overheating.

4.1. *The reporting of overheating by older people*

This research has shown, perhaps more clearly than before, the consequences of using self-reporting as an indicator of the prevalence of overheating in the homes of older people.

Based on the self-reports of overheating, one would conclude that the prevalence of overheating in the English stock is much less in households

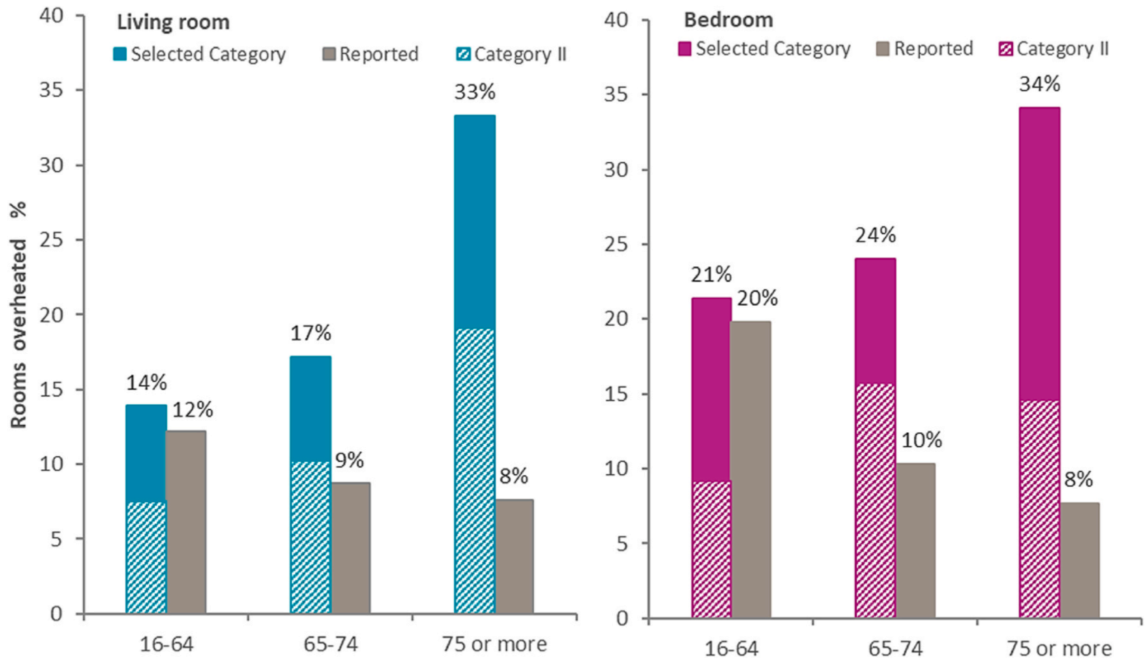

Fig. 10. Monitored and self-reported prevalence of summertime overheating in living rooms and bedrooms by age of household representative person.

with elderly persons, than in households with younger adults; 60% less in the bedrooms of over 75's compared with the bedrooms of those under 64. One would thus presume that the elderly are at much less risk of overheating than others. However, in reality, the prevalence of monitored overheating in the homes of the elderly is far higher than in homes with younger household members: overheating in the bedrooms of the elderly is 50% greater, and in the living rooms more than double. This difference is not simply because the analysis method accounted for the added heat-sensitivity of the elderly (Sel. Cat.). The dwellings occupied by the elderly were also inherently more likely to overheat (Cat.II analysis). These results may be because the elderly do not perceive the heat, a trait that others conducting field surveys have observed (eg. [54,55]), or because they desire higher temperatures, which are are classed as overheating by the adaptive criteria. Also contributing is that older people are more likely to be both cognitively and physically less able to plan and execute mitigation measures that would control summer heat, e.g., through ventilation and the operation of curtains and blinds. This study, and previous work [12] has also noted that the continuance of heating through the summer is most often observed in the homes of the elderly.[36] The combined effect of the impaired ability of the elderly to detect the heat, the type of dwellings they live in, their potential inability to 'manage heat', their likely preference for higher temperatures and their heightened heat-sensitivity renders older people especially at risk of harm in hot weather[37] (e.g., [6]). During the four heat waves of 2018, 80% of the excess deaths were persons aged over 65 [8].

Most previous field studies have not considered the differential sensitivity to heat of different households, even though adaptive thermal comfort standards enable this. By analysing the monitored data using the Sel.Cat. approach (Cat.I if the household has heat-sensitive members and Cat.II if not), a more realistic impression of the impacts of elevated indoor temperatures is obtained. The prevalence of overheating in English living rooms more than doubled when heat-sensitivity was accounted for (Fig. 1). By also using a Cat.II threshold for all homes, the inherent tendency of dwellings to overheat by virtue of their thermal characteristics and the way they are operated could also be discerned. This dual approach also enabled identification of sectors of the housing stock where overheating occurred due to a combination of occupants' heat-sensitivity and the characteristics of the dwelling, most notably in social housing.

These observations have implications for the conduct of future overheating studies in which elderly persons might participate and for any actions taken to mitigate overheating. Firstly, whilst questionnaires are a useful tool for identifying thermal discomfort or the prevalence of overheating, these need to be used with care; they are likely to underestimate the general prevalence of overheating and, more seriously, in the context of older people the results could be misleading. Secondly, the reliability of the upper-bound adaptive thermal comfort thresholds might usefully be revisited specifically for the case of the elderly. Thirdly, if heat mitigation measures are focussed on dwellings where there is a high propensity for living rooms to overheat, notably flats and bungalows, then the elderly and vulnerable, who are more likely to occupy such dwellings, would be particular beneficiaries. Fourthly, heat health campaigns and other initiatives could usefully target the elderly, with health care visitors, family members and other carers being alerted to the dangers of heat and primed to take appropriate action. Here we have in mind tailored advice, in addition to general national heatwave warnings. Beyond this, assisted living and smart home technology could be used to provide heat-warnings to carers based on monitored temperatures (e.g., [56]). There is valuable research to be done to understand how the elderly, and indeed other households, manage the passive heat mitigation measures at their disposal and thus how such advice might best be framed.

4.2. Overheating criteria for bedrooms

This research has revealed more clearly than before the substantial difference between the estimates of bedroom overheating as indicated by a fixed, static criterion (26 °C/1%) and both the self-reported overheating and estimates based on the adaptive thermal comfort model. In

[36] In the 2017 EFUS sample, there was evidence of summertime heating in around 55% of homes. The elderly appear less likely to turn down the thermostat or turn off the boiler at the end of winter. The effect is to prevent rooms cooling below the heating set point and so thermal mass does not discharge at night and so acts as a less effective thermal buffer during the subsequent day.

[37] The UK Housing Health and Safety Rating System [63] recognises that a person aged 65 years or over is most at risk of harm from excessive heat.

the adaptive model, the threshold at which hours of overheating are accrued rises as the summer warms and heat waves strike, in this work up to 30 °C (Cat.II) for one dwelling in London, i.e., well above 26 °C. Other researchers have also reported a very high prevalence of overheating as judged by static criteria, they have also, therefore, resorted to using an adaptive model (drawn from either TM52 or TM59, or from ASHRAE 55) to assess overheating in bedrooms [40,49,50,57,58]. Static criteria, which may well provide a reasonable overheating threshold for the design of new homes, are clearly proving problematic for the credible determination of overheating in existing homes based on monitoring.

It is worth noting here that the static threshold of 26 °C, originated from data collected from just 21 adults by Humphreys in 1975 [59].[38] Today, bedwear and bedding are very different and year-round bedroom temperatures are generally higher. Interestingly, the 1975 findings were challenged immediately after they were presented. Wyon observed that those surveyed slept with tucked-in sheets and blankets whereas elsewhere in Europe people slept under duvets which permit '*minute by minute*' adaptation[39] [60]. Nicol and Humphreys himself [24] have observed that the static criterion may not reflect the effects of temperature on sleep today.

In this work, for want of a better option, and following the steer of others, the same adaptive criterion as used in living rooms was adopted for bedrooms. The similarities in the patterns of bedroom overheating between the adaptive model and the self-reports of households provides some confidence that the approach has merit. Whether the adaptive temperature thresholds change with outdoor temperature at the correct rate, whether the thresholds are set at the correct level, whether the thresholds continue to rise even at higher ambient temperatures,[40] or whether a 3% exceedance, or indeed any exceedance, is appropriate for assessing bedrooms are all matters worthy of debate.[41] That an adaptive criterion is worth exploring is surely not?

4.3. Thermal physics and the prevalence of overheating

By using the same adaptive overheating criterion for both living rooms and bedrooms, this work has shown that monitored overheating is more prevalent in bedrooms at night than in living rooms during the day. This phenomenon was observed in all dwellings except flats and bungalows. The households also reported a higher prevalence of overheating in bedrooms. Previous researchers have made similar observations (e.g., [49,50,57,61]).

The phenomenon can be explained by the thermal physics at play. In two (or more) storey houses the ground floor is more shaded by the surrounding environment than the upper (bedroom) floor and so may have less solar heat gain. The ground floor may also be thermally more heavyweight, having a solid floor. Warm air generated during the day, will rise to the spaces above and at night, cool air, which is admitted to provide cooling, is more likely to pool on the ground floor. The bedrooms in contrast, may be less shaded from the sun, are more likely to be thermally lightweight and may be directly below the hot roof or loft/attic space. Occupant behaviour may also be a factor, during the day, occupants are more likely to 'manage' curtains and blinds on the ground floor than in the bedrooms above. And opening windows whilst awake is less of a security risk than is opening them at night. In flats and bungalows however, both rooms are on the same level, and not necessarily on the ground floor, so there are fewer, if any, systematic differences between the thermal physics at play in the two rooms.

The presence of energy efficiency measures, loft insulation, double glazing and wall insulation, had no significant impact on the prevalence of monitored overheating in either room. Although double glazing tended to increase the prevalence of overheating the result was not significant. Glazing makes a relatively small contribution to the thermal insulation of a dwelling envelope, however modern glazing systems might: restrict ventilation (less air leakage; removal of pre-existing trickle vents; and a lack of small, secure, openings); be more difficult to operate, especially for elderly persons; and be associated with other changes to the dwelling, such as the addition of conservatories, which reduce ventilation potential. Glazing and heat mitigation is a matter worthy of further investigation.

The prevalence of overheating in the living rooms of dwellings with a good energy efficiency rating (bands A to C) was significantly greater than in less efficient dwellings (bands D to F). However, this was simply because the more efficient dwellings were significantly more likely to be flats (see also [62]), which are inherently more likely to overheat (see e.g., [11]). The observation that fabric energy efficiency measures do not necessarily increase the risk of overheating risk is encouraging from the perspectives of both climate change mitigation and adaptation. However, continued vigilance, e.g., through monitoring studies, is recommended to ensure that the efficiency measures needed to address the UK's zero-carbon goals do not have unintended consequences.

4.4. Recommendations for future studies

The hot summer of 2018 precipitated widespread overheating which, together with the large sample of monitored homes, enabled statistical significance tests to clearly identify the characteristics of dwellings and households that experience a higher prevalence of overheating, both as measured and as reported. The rich dataset offers opportunities for further useful analysis. Future studies of this type will help to track the prevalence of overheating as the climate warms.

There were however some difficulties and limitations. In particular, the questionnaire that captured the reports of overheating from occupants was not delivered at the same time as the measured temperatures. Contemporaneous measured and reported data would aid our understanding of overheating perception by different people. It would also aid the design of credible overheating criteria for bedrooms in existing homes. However, careful consideration of the role of questionnaire surveys for assessing overheating is needed in the light of our results for older people.

The work hints at the possibility of monitoring temperatures over a shorter time period yet still achieving an accurate picture of the patterns of overheating. More subtly, perhaps the method of weighting dwellings to scale to the national stock requires further consideration so that the weighting parameters aligned with factors that impact on overheating. Finally, of course, correlations between overheating and dwelling and household characteristics does not imply causation.

5. Conclusions

The prevalence of overheating in the living rooms and bedrooms of homes during England's hottest ever summer, 2018, has been measured. This provides a glimpse of the likely prevalence of overheating in the national stock during a summer typical of the 2050's. The patterns of overheating with dwelling and household characteristics were also analysed and compared to the patterns of overheating reported by households during the warm summer of 2017. The results have implications for the 'measurement' of overheating, and policies and practices

[38] By today's standards this is weak basis on which to found industry guidance.

[39] Our own experience tells us that we adapt both before sleep, e.g., by choosing our bedding and bedwear and opening or closing windows, and during sleep, e.g., by curling up or stretching out, sticking our limbs out from the duvet, by moving closer to, or further away from a warm bed partner, etc; might these adaptations be made without unduly affecting our sleep quality?

[40] Adaptation during sleep is probably limited to room temperatures in the region of 29–32 °C, which is approximately the temperature that sleeping persons prefer around their body.

[41] Or, as [64] put it, '*It is likely that temperature thresholds will vary according to different settings, population groups and individual thermal comfort preferences, and therefore, it is noted that one single threshold may not be sufficient for policy*'.

adopted to mitigate overheating risk in existing homes. The observations made here for the English housing stock are likely to have implications for heat mitigation in housing stock in other temperate regions.

5.1. Measuring summertime overheating

1. The standard static overheating criterion used in the UK to define bedroom overheating produced implausibly high overheating estimates. Further analysis was therefore undertaken using the same adaptive overheating criterion, from CIBSE TM52, to calculate the daytime overheating in living rooms and the night-time overheating in bedrooms. It is recommended that the static criterion is replaced by a well-founded, adaptive criterion, which addresses the impact of heat on sleep quality.
2. The headline analysis of overheating accounted for the differing heat-sensitivities of households, thus providing the most credible estimate of the prevalence of overheating in English living rooms and bedrooms. To compare the inherent tendency of different categories of dwellings to overheat, the heat sensitivity of the occupants was ignored. This dual approach is recommended for future field surveys.
3. The assessment of overheating using the TM52 adaptive criterion requires monitoring for five months (May to September). Comparisons with monitored results undertaken for the shorter summer period (June to August) produced similar patterns of overheating in both living rooms and bedrooms as the dwelling and household characteristics changed. The characteristics for which there were significant differences in the incidence of overheating were also virtually the same for both monitoring periods. It may be possible to reliably assess overheating risks by monitoring over shorter time periods.

5.2. Patterns of overheating in the English housing stock

4. During 2018, in England as a whole, monitoring indicated that 3.6 million homes (15%) had living rooms that overheated and 4.6 million (19%) had overheated bedrooms. In the summer of 2017, which was not as hot, 2.5 million living rooms (11%) and 3.8 million bedrooms (17%) were reported as uncomfortably warm often or all the time, i.e., overheated.
5. Overall, and for nearly all dwelling characteristics, the reported and monitored prevalence of overheating in bedrooms was greater than in living rooms. Only in flats and other single storey dwellings, e.g., bungalows, was a different tendency observed. These results could be explained by the thermal-physics at play in single and two, or more, storey dwellings.
6. In general, the patterns of reported overheating in living rooms as the characteristics of the dwelling and household changed was similar to the monitored pattern of overheating. However, whereas the prevalence of reported overheating in both rooms was significantly less where the household representative person was over 75, the monitored prevalence of overheating was greater, significantly so for the living rooms.
7. As monitored and as reported, there was a significantly greater prevalence of overheating in living rooms and bedrooms in London than in other English regions.
8. As monitored and as reported, there was a significantly greater prevalence of overheating in the living rooms of flats and small dwelling (i.e., with a floor area less than 50 m^2), compared to other dwelling types. The monitored and reported prevalence of overheating in flats was roughly double that for other dwelling types and the prevalence in small dwellings roughly four times higher than in dwellings over 100 m^2.
9. As monitored and as reported, households with an income in the lowest 40%, or who live in social housing rather than in private housing, were significantly more likely to experience overheating in both living rooms and bedrooms than other households. These tendencies were primarily due to the additional heat sensitivity of household members but both rooms in social housing were inherently more likely to overheat.
10. The more affluent members of society, people under 65, and those living in larger homes, were significantly less likely to experience summertime overheating.
11. The prevalence of reported overheating in living rooms was significantly less in dwellings with 50 mm or more of loft insulation. There was no significant difference in the measured overheating of living rooms or bedrooms with changes in any fabric energy efficiency measures. There was a higher prevalence of both monitored and reported overheating in the living rooms of homes with a better overall energy efficiency rating (i.e., SAP rating bands A to C, cf. rating bands D to G). This is likely to be because a significantly greater number of homes with a high energy efficiency rating are flats, which are inherently more prone to overheating.

5.3. Implications for overheating mitigation policies and practice

12. Future surveys to assess the extent of overheating in homes should treat with caution the self-reports of overheating made by people over 65. The reports may fail to identify people suffering from overheating. Monitoring studies are a more robust approach.
13. Fabric energy efficiency measures aimed at reducing the wintertime energy demands of English dwellings, did not significantly increase the prevalence of overheating. However, continued vigilance is needed to ensure that climate change mitigation measures do not have unintended consequences such as summertime overheating.
14. The fact that bedrooms overheat more at night than living rooms do during the day, even though outdoor temperatures are lower at night, is an important finding from this research. Public health advice might usefully recommend that households 'manage' bedrooms during the day to prevent heat build-up.
15. Around two thirds of overheated living rooms and bedrooms were in London and, nationally, around two thirds of overheated living rooms were in flats. Overheating mitigation measures might therefore focus on flats, and other small dwellings, especially those in London.
16. Those in society who are most disadvantaged, the poor, those living in social housing, the elderly and the unemployed, disproportionately suffer from overheated homes. Mitigation measures, and help and support during heat waves, ought to focus on this sector of the population.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Influence of Dwelling and Household Characteristics on the prevalence of Overheating in Living rooms and Bedrooms

The data for the categories where there is a significant difference in the prevalence of overheating in living rooms and bedrooms with the dwelling and household characteristics are given in the tables below. These results provide the basis for the narrative in Section 3 of this paper. In all cases the results are based on temperatures measured between May and September 2018 analysed using the adaptive thermal comfort, Sel.Cat., approach. The '*Number (000s)*' for each characteristic is the weighted sample size that represents the numbers in the English housing stock, see Section 2.4. The percentage of the English stock and lower and upper confidence limits (LCL, UCL) are listed.

The supplementary information to this paper [52] gives the results for all dwelling and household categories whether or not the results are significant. It contains the results when all homes are assumed to be Cat.II and for data measured only during the summer (June to August). It also contains the results for the self-reported prevalence of overheating.

In this Appendix and the supplementary information, the categories for which there are significant differences are identified using a Chi-Squared test. Results significant at the 1% level are in bold in the 'Sig.' column, results significant at the 5% level are in ***bold italic***. The characteristics in the same category, not sharing the same subscript in the '*fail, sample size'* column, have a significantly different prevalence of overheating ($p < 0.05$), as indicated by a two-sided test of equality. These Z-tests are adjusted for all pairwise comparisons within each category using the Bonferroni correction.

A1: The influence of dwelling characteristics on overheating in living rooms

		Adaptive criterion 1 (Sel.Cat.) in living room, May–Sep											
		Pass					Fail					Sig.	Chi-square
		Sample size	Number (000s)	Percent (%)	LCL (%)	UCL (%)	Sample size	Number (000s)	Percent (%)	LCL (%)	UCL (%)		
Dwelling type	End terrace	$58_{a,b}$	1746	86.0%	72.1%	94.4%	$6_{a,b}$	284	14.0%	5.6%	27.9%	0.003	17.663
	Mid terrace	$96_{a,b}$	3230	87.7%	78.5%	93.9%	$13_{a,b}$	452	12.3%	6.1%	21.5%		
	Semi detached	149_{a}	4666	90.4%	83.6%	95.0%	25_{a}	494	9.6%	5.0%	16.4%		
	Detached	89_{a}	3445	90.0%	82.1%	95.1%	11_{a}	382	10.0%	4.9%	17.9%		
	Bungalow	$42_{a,b}$	1090	75.5%	60.8%	86.7%	$17_{a,b}$	354	24.5%	13.3%	39.2%		
	Flat	73_{b}	2323	70.4%	59.3%	79.9%	37_{b}	977	29.6%	20.1%	40.7%		
House or flat	House or bungalow	434_{a}	14,176	87.8%	83.9%	91.0%	72_{a}	1966	12.2%	9.0%	16.1%	0.000	13.210
	Flat	73_{b}	2323	70.4%	59.3%	79.9%	37_{b}	977	29.6%	20.1%	40.7%		
Useable floor area – banded (m^2)	<50	44_{a}	1322	65.1%	50.3%	77.9%	25_{a}	710	34.9%	22.1%	49.7%	0.002	17.437
	50 to 69	138_{b}	4279	86.6%	79.2%	92.0%	30_{b}	664	13.4%	8.0%	20.8%		
	70 to 89	$141_{a,b}$	3919	84.4%	76.5%	90.4%	$27_{a,b}$	724	15.6%	9.6%	23.5%		
	90 to 109	$81_{a,b}$	3020	84.6%	73.8%	92.1%	$19_{a,b}$	549	15.4%	7.9%	26.2%		
	110 or more	103_{b}	3958	93.0%	86.4%	97.0%	8_{b}	296	7.0%	3.0%	13.6%		
Government Office Region EHS version	London	36_{a}	1623	71.9%	54.7%	85.1%	18_{a}	636	28.1%	14.9%	45.3%	0.009	6.876
	Other regions	471_{b}	14,876	86.6%	82.8%	89.7%	91_{b}	2307	13.4%	10.3%	17.2%		
Energy ffic. rating band (SAP 2012)	A/B/C	129_{a}	4415	79.2%	71.3%	85.8%	39_{a}	1159	20.8%	14.2%	28.7%	*0.047*	3.962
	D/E/F/G	378_{b}	12,084	87.1%	82.8%	90.7%	70_{b}	1785	12.9%	9.3%	17.2%		

A2: The influence of dwelling characteristics on overheating in bedrooms

		Adaptive criterion 1 (Sel.Cat.) in bedroom, May–Sep											
		Pass					Fail					Sig.	Chi-square
		Sample size	Number (000s)	Percent (%)	LCL (%)	UCL (%)	Sample size	Number (000s)	Percent (%)	LCL (%)	UCL (%)		
Government Office Region EHS version	London	30_{a}	1446	68.4%	50.3%	83.0%	19_{a}	668	31.6%	17.0%	49.7%	*0.021*	5.336
	Other regions	430_{b}	13,923	83.0%	78.9%	86.6%	112_{b}	2855	17.0%	13.4%	21.1%		

A3: The influence of household characteristics on overheating in living rooms

		Adaptive criterion 1 (Sel.Cat.) in living room, May–Sep											
		Pass					Fail					Sig.	Chi-square
		Sample size	Number (000s)	Percent (%)	LCL (%)	UCL (%)	Sample size	Number (000s)	Percent (%)	LCL (%)	UCL (%)		
Tenure	Private	342_{a}	13,922	87.1%	82.9%	90.6%	56_{a}	2057	12.9%	9.4%	17.1%	0.007	7.309
	Social	165_{b}	2577	74.4%	67.1%	80.8%	53_{b}	886	25.6%	19.2%	32.9%		

(*continued on next page*)

(*continued*)

		Adaptive criterion 1 (Sel.Cat.) in living room, May–Sep											
		Pass					Fail					Sig.	Chi-square
		Sample size	Number (000s)	Percent (%)	LCL (%)	UCL (%)	Sample size	Number (000s)	Percent (%)	LCL (%)	UCL (%)		
Household member over state pension age	No	317_a	11,643	89.0%	84.5%	92.5%	54_a	1438	11.0%	7.5%	15.5%	0.001	10.924
	Yes	190_b	4857	76.3%	69.8%	82.1%	55_b	1506	23.7%	17.9%	30.2%		
Age of HRP	16–64	333_a	12,221	89.2%	84.9%	92.7%	55_a	1472	10.8%	7.3%	15.1%	0.000	18.970
	65–74	$114_{a,b}$	2445	81.4%	73.3%	87.8%	$26_{a,b}$	560	18.6%	12.2%	26.7%		
	75 or more	60_b	1834	66.8%	55.4%	76.9%	28_b	911	33.2%	23.1%	44.6%		
After housing costs equivalised income - weighted quintiles	1st or 2nd	271_a	6066	77.6%	71.4%	83.0%	71_a	1747	22.4%	17.0%	28.6%	0.001	10.816
	3rd to 5th	236_b	10,433	89.7%	85.1%	93.3%	38_b	1197	10.3%	6.7%	14.9%		
Anyone in household with long term illness or disability or HRP/partner registered disabled?	No	292_a	10,597	89.3%	84.8%	92.9%	45_a	1263	10.7%	7.1%	15.2%	0.002	9.767
	Yes	214_b	5889	77.8%	71.3%	83.4%	64_b	1680	22.2%	16.6%	28.7%		
Is anyone in household employed?	No	213_a	5043	76.4%	70.2%	81.9%	64_a	1556	23.6%	18.1%	29.8%	0.001	11.301
	Yes	294_b	11,457	89.2%	84.6%	92.8%	45_b	1387	10.8%	7.2%	15.4%		

A4: The influence of household characteristics on overheating in bedrooms

		Adaptive criterion 1 (Sel.Cat.) in bedroom, May–Sep											
		Pass					Fail					Sig.	Chi-square
		Sample size	Number (000s)	Percent (%)	LCL (%)	UCL (%)	Sample size	Number (000s)	Percent (%)	LCL (%)	UCL (%)		
Tenure	Private	318_a	13,075	83.5%	78.9%	87.4%	73_a	2587	16.5%	12.6%	21.1%	*0.018*	5.569
	Social	142_b	2294	71.0%	63.0%	78.1%	58_b	936	29.0%	21.9%	37.0%		
EFUS reported household composition	couple, no dependent child(ren) under 60	57_a	2966	91.9%	81.7%	97.3%	8_a	262	8.1%	2.7%	18.3%	0.001	24.016
	couple, no dependent child(ren) 60 or over	$104_{a,b}$	2755	81.7%	73.2%	88.4%	$28_{a,b}$	618	18.3%	11.6%	26.8%		
	couple with dependent child(ren)	89_b	2737	65.0%	54.8%	74.3%	44_b	1472	35.0%	25.7%	45.2%		
	lone parent dependent child(ren)	$45_{a,b}$	1354	87.0%	72.9%	95.2%	$9_{a,b}$	202	13.0%	4.8%	27.1%		
	other multi-person households	$31_{a,b}$	1232	84.8%	66.9%	94.9%	$11_{a,b}$	221	15.2%	5.1%	33.1%		
	one person under 60	$44_{a,b}$	1812	92.6%	79.4%	98.2%	$7_{a,b}$	146	7.4%	1.8%	20.6%		
	one person 60 or over	$90_{a,b}$	2512	80.7%	71.2%	88.0%	$24_{a,b}$	602	19.3%	12.0%	28.8%		
Number of persons in the household	1	134_a	4279	85.3%	77.8%	91.0%	31_a	735	14.7%	9.0%	22.2%	0.000	17.665
	2	192_a	6762	88.3%	82.5%	92.7%	38_a	892	11.7%	7.3%	17.5%		
	3 or more	134_b	4327	69.5%	61.0%	77.2%	62_b	1895	30.5%	22.8%	39.0%		
Children present?	No children	353_a	11,965	85.4%	81.0%	89.2%	88_a	2042	14.6%	10.8%	19.0%	0.001	12.002
	At least one child	107_b	3404	69.7%	60.1%	78.1%	43_b	1481	30.3%	21.9%	39.9%		
After housing costs equivalised income - weighted quintiles	1st or 2nd	245_a	5904	76.2%	69.8%	81.8%	84_a	1842	23.8%	18.2%	30.2%	*0.031*	4.628
	3rd to 5th	215_b	9465	84.9%	79.5%	89.4%	47_b	1681	15.1%	10.6%	20.5%		
Anyone in household with long term illness or disability or HRP/partner registered disabled?	No	271_a	9970	85.1%	79.9%	89.4%	56_a	1744	14.9%	10.6%	20.1%	*0.017*	5.673
	Yes	189_b	5398	75.4%	68.5%	81.4%	74_b	1766	24.6%	18.6%	31.5%		
Is the household Under-Occupying?	No	321_a	9867	77.5%	72.2%	82.3%	104_a	2858	22.5%	17.7%	27.8%	0.006	7.583
	Yes	139_b	5502	89.2%	82.9%	93.8%	27_b	665	10.8%	6.2%	17.1%		

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