Summertime overheating in UK homes: is there a safe haven?

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ABSTRACT
Summertime overheating in dwellings in temperate climates is widespread. Overheating in bedrooms disrupts sleep, degrading health and wellbeing, and can be life-threatening. Air-conditioning homes is a solution, but is expensive and adds load onto electricity networks. An alternative is to provide safe havens, a cool retreat for sleeping when the main bedroom overheats. This paper estimates the number of English dwellings that might already have such spaces. The 2017 Energy Follow Up Survey (EFUS) to the English Housing Survey (EHS) provides temperatures measured in the main bedroom, up to two other bedrooms and the living room of 750 homes. These data were collected in 2018, a summer typical of those expected in the 2050s. The main bedroom overheated in 19% of the housing stock as judged by an adaptive comfort criterion. Up to 76% of these homes had living rooms that could provide a safe haven, and in up to 46% an alternative bedroom might provide a safe haven. Very few, if any, flats and small-area dwellings had a safe haven. These figures provide an upper-bound estimate; in practice the useable number of safe havens is likely to be less.

POLICY RELEVANCE
Safe havens for use during heatwaves have been suggested as a climate-adaptive strategy to ameliorate indoor overheating. In this study, the prevalence of safe havens, which can be slept in when the main bedroom overheats, is estimated. Living rooms offered the best opportunity of a safe haven for sleeping, with 5.8 million of the 7.4 million people experiencing an overheated main bedroom being relieved of exposure. Flats and small dwellings were more prone to overheating, but few, if any, had either a living room or a spare bedroom that offered a safe haven. Overall, this study strengthens the idea that public health advice, especially during heatwaves, should be tailored to different dwelling and household types. For larger dwellings other than flats, advice could emphasise the benefits of sleeping in the living room, where possible, on hot nights. Homes without safe havens should be the focus of heat mitigation retrofit strategies.
1. INTRODUCTION

The threats posed by climate change are of worldwide concern. Global temperatures are likely to be 1.5°C above pre-industrial levels by 2052 (IPCC 2018); and heatwaves will increase in frequency, intensity and duration (Christidis et al. 2015). High summertime temperatures are linked to excess mortality and morbidity (Arbuthnott & Hajat 2017; Hajat et al. 2014; Ormandy & Ezratty 2012), and the majority of fatal heat exposures in developed nations occur indoors (Quinn et al. 2014). The elderly and very young, those with chronic physical and/or mental health conditions, and the immobile and bed-ridden are especially vulnerable (Ormandy & Ezratty 2016; Vandentorren et al. 2006). ‘The average number of heat-related deaths in the UK is expected to more than triple, to 7,000 a year by the 2050s’ (House of Commons 2018: 3).

In developed countries with hot summers, air-conditioning is widespread, but there are concerns about the summertime resilience (e.g. Baniassadi et al. 2018) to power losses and extreme weather events (e.g. EOP 2013; Nahlik et al. 2017). In temperate climates there are concerns that an upsurge in use will increases the summertime loads on local and national electricity supply networks (Crawley et al. 2020). The costs of buying and operating air-conditioning systems will bear most heavily on the poorest in society, introducing the prospect of summertime fuel poverty (CCC 2019a). And air-conditioning ejects waste heat into the environment contributing further to the urban heat-island effect (CCC 2019b).

In many regions where domestic air-conditioning is rare, summertime overheating is becoming increasingly common, e.g. in France and Germany (MHCLG 2019a), the northern US (Williams et al. 2019a), the UK and New Zealand (Lomas & Porritt 2017). In the UK, overheating occurs in homes across all regions (Beizaei et al. 2013), including Scotland (Morgan et al. 2017). A recent study (Lomas et al. 2021) indicated that in the hot summer of 2018, 15% (3.6 million) English homes\(^1\) (Figure 1) had overheated living rooms and 19% (4.5 million) overheated bedrooms. Flats and small dwellings in London and the South East are especially at risk of overheating, as are the homes of society’s most vulnerable citizens.

Passive measures such as ventilation and shading are the commonly recommended strategies for reducing overheating (CCC 2019b; CIBSE 2013; Lomas 2021). A 2017 questionnaire survey (BEIS 2021a) revealed that 44% of English households used no cooling equipment, 50% used portable fans and just 2% reported using a fixed or portable air-conditioning unit. However, in warmer regions and in some noisy, polluted cities the drive to air-condition new and existing homes may become irresistible. In the UK, the demand for domestic air-conditioning units grew by 17% between 2011 and 2017 (CCC 2019b). Estimates of the likely uptake of air-conditioning in the UK by 2050 vary widely, e.g. from 5% to 32% in Crawley et al. (2020).

High night-time temperatures in bedrooms are a particular concern. They can limit a person’s ability to recover from heat stress experienced during the day (Kovats & Hajat 2008) and so have been identified as a significant contributing factor to heat-related mortality (Anderson et al. 2013), especially in the elderly (Murage et al. 2017). Bedroom temperatures are, therefore, seen by some as the most important metric in domestic overheating assessment (Peacock et al. 2010). In the hot summer of 2018, many English homes had bedroom temperatures at night that were higher than the living room temperatures during the day (Lomas et al. 2021). Elevated night-time temperatures can degrade ‘sleep adequacy’ in working-age adults (Obradovich et al. 2017) and ‘sleep quality’ in older people (Williams et al. 2019b) and can exacerbate pre-existing sleep disorders in all age groups (Rifkin et al. 2018). Degraded sleep quality has direct implications for the efficiency of daytime performance, accident risk and workplace productivity (Hillman et al. 2018; Alhola & Polo-Kantola 2007).

Whilst fans or air-conditioning can improve thermal comfort, others have proposed the concept of a safe haven or ‘cool retreat’ as an important aspect of making dwellings resilient to future climate conditions (Ormandy & Ezratty 2016; Zuo et al. 2015). Indeed, daily movement between spaces to seek comfort for sleeping is a common adaptive behaviour in many parts of the world with hot climates (Nicol et al. 2012). The safe haven may be cooler due to the peculiarities of the building, its construction, internal layout and orientation, or, as in Palmer et al. (2014), a deliberate attempt to adapt dwellings by ‘designing’ a cooler space.
By encouraging spatial adaptation, it may be possible to preserve sleep quality during heatwaves without recourse to energy-intensive methods. In fact, in response to the severe European heatwave of 2003 (Vandentorren et al. 2006), Public Health England (PHE) published an annual heatwave plan which is intended to ‘protect the population from heat-related harm to health’ (PHE 2019: 4). One suggestion given is that ‘If possible, move into a cooler room, especially for sleeping’ (PHE 2019: 28). But do English homes have cooler sleeping rooms and if they do, which rooms are they and in which homes are they to be found?

Previous field studies have, understandably given limited resources, focused on monitoring temperatures in only the living room and main bedroom (e.g. Beizaee et al. 2013; Lomas & Kane 2013; Petrou et al. 2019). Sometimes, information about sleep and heat is obtained from interviews and other social survey methods (e.g. Hulme et al. 2013; Khare et al. 2015; Raw 2018). Using data from the 2017 Energy Follow Up Survey (EFUS), this research examines temperatures measured in multiple spaces during the hot summer of 2018. This was England’s joint hottest summer on record and included four heatwaves. The recorded temperatures were typical of those predicted for summers in the 2050s (McCarthy et al. 2019). The data thus present a unique opportunity to take a forward look at the incidence of overheating that will be normal in English homes 30 years from now.

**Figure 1:** English dwelling types.
The present research seeks to identify whether, in English homes with an overheated main bedroom, there is a safe haven, i.e. a space that is not deemed to overheat as judged by contemporary criteria. The three research questions being addressed are as follows:

- In what percentage of English homes with an overheated main bedroom does either the living room or an alternative bedroom provide a safe haven?
- If people switch nightly between the main bedroom and either a cooler living room or a cooler alternative bedroom, what percentage of English homes are deemed to have a safe haven?
- For which households, living in which dwellings are safe havens most prevalent, and in which are they least prevalent?

The results shed light on the veracity and value of the prevailing heatwave advice and the prospects that such advice has for curbing the uptake of air-conditioning in English bedrooms.

2. METHODS

The study is based on further analysis of the temperatures monitored in English homes as part of the 2017 EFUS. The method of recruitment and the survey, questionnaire and monitoring methods are described fully elsewhere (BEIS 2021a, 2021b). To investigate the prevalence of safe havens, the temperature data from the rooms in each dwelling were matched with the ambient temperature measured at a near-by weather station. The monitored data were then cleaned, and two samples of reliable data created, one for the main bedroom and living room, and one for the main bedroom and at least one other bedroom. Weighting factors were then applied to the homes in each sample so that the results could be scaled to the English stock as a whole. Brief details of these processes are provided below along with an explanation of the method used to assess bedroom overheating.

2.1 THE EFUS DATA SET

The households recruited to the 2017 EFUS were sampled from those that participated in English Housing Surveys (EHSs) boosted by households surveyed in earlier EHSs which, at the time, had been modelled as being in fuel poverty (MHCLG 2020). As part of the EFUS project, room temperatures were monitored during the summer of 2018.

The surveys and questionnaires undertaken as part of the EHS enabled the dwellings and households to be categorised and, within each category, various characteristics were defined. For all the categories and characteristics considered in the EFUS study, see the methodology report (BEIS 2021b). In this work, three dwelling categories were adopted: dwelling age (six age bands); usable floor area (five size bands); and dwelling type (terraced, semi-detached, detached, bungalow and flat/apartment) (Figure 1). Four household categories were examined: tenure (rented, privately owned); occupancy (fully occupied or under-occupied); household composition (six characteristics); and the age of the household representative person (five age bands). For further details, see Tables A1 and A2 in the supplemental data online. These are a subset of the categories and characteristics used in previous work (Lomas et al. 2021).

For households that consented, temperature loggers 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). Some householders declined to have loggers in rooms other than the living room and main bedroom. The loggers, which had an accuracy of ±0.4°C (Tinytag 2015), were deployed between August and October 2017 and recorded temperatures at half-hourly intervals until April 2019. The loggers from 750 households were, after the initial data cleaning, considered suitable of further analysis.

The monitored temperatures covered the calendar year 2018, the summer of which was ‘the joint hottest summer season (June, July, August) in the Met Office UK national temperature series’ (Holles et al. 2019, cited in McCarthy et al. 2019: 390); ‘and it was the warmest on record for England’ (McCarthy et al. 2019: 390). There were four heatwaves between 25 June and 9 August,
which lasted between three and 11 days (Figure 2b). The highest temperatures occurred during the third heatwave (Figure 2a), which resulted in ‘an estimated 409 excess deaths observed above baseline in the 65+ year olds’ (PHE 2018: 4).

![Figure 2: Temperatures measured in 2018: (a) during the longest and most severe heatwave; and (b) between May and September showing: the outdoor temperature; the four heatwaves; the daily running mean of the outdoor temperature ($T_{rm}$); the adaptive thermal comfort thresholds for Category I and II households; and the measured half-hourly temperatures in the main bedroom (Bedroom 1) and an alternative bedroom (Bedroom 2).](image)

Detailed analyses by the UK Meteorological Office (McCarthy et al. 2019: 396) conclude ‘that a 2018-like summer could be more common than not by the mid-twenty-first century’, thus Madge (2019: n.p.) observed that ‘these summer temperatures could be normal by the 2050s’.

To enable the overheating assessment, each dwelling in the EFUS data set was paired with its nearest British Atmospheric Data Centre weather station (Met Office 2012). Around 150 weather stations were used, with each station paired, on average, with five dwellings. The highest recorded outdoor temperature at these stations was 34.4°C on 26 July near a dwelling in Surrey.

2.2 DATA CLEANING AND WEIGHTING

Following the procedure already established for the living room and main bedroom (Lomas et al. 2021), the data from additional bedrooms were also collated, cleaned and examined. In brief, the measured half-hourly values for the period from May to September were plotted alongside the weather data and inspected by eye. Bedrooms were removed from the sample if: no temperatures were recorded; there were inexplicable temperature spikes or changes in the general form of the temperature trace; multiple sensors had recorded the same temperatures; or due to other ‘strange’ anomalies.

Following cleaning, there were 591 homes with good data for the main bedroom. Of these, 553 had good data for the main bedroom and living room. This latter sample, herein called the ‘living room sample’ was used to examine the prevalence of safe havens provided by living rooms.

To create a sample that could be used to explore the prevalence of safe havens provided by sleeping in a different, cooler bedroom, the 283 homes with good data for the main bedroom and at least one other bedroom were used. Such a sample would, however, overestimate the efficacy of nationwide heatwave advice to sleep in another bedroom because it does not include dwelling
where there is no second bedroom. The sample was therefore seeded with data from 25 randomly selected smaller homes (< 50 m²) for which there were only main bedroom temperatures. This ‘bedroom sample’ consisted of 308 dwellings.

In both samples, there was always 20 homes or more with a particular characteristic (see Tables A1 and A2 in the supplemental data online) which enabled an insightful analysis to identify the impact of characteristics on the prevalence of safe havens.

To scale the results for each sample of dwellings up to the English national stock, 23.95 million dwellings and 23.27 million households in 2017 (MHCLG 2019b, 2019c), the homes were weighted such that each home represented between 4000 and 225,000 other English homes (see tables in the supplemental data online).

Following the weighting procedure, for both samples the percentage of dwellings with particular characteristics (see Table A1 in the supplemental data online) and households with particular characteristics (see Table A2 online) are, in general, similar to those reported for the 2017 English stock as a whole (cf. columns 7 and 8 with column 6 in Tables A1 and A2 online). However, the percentage of flats is under-represented in both the living room and bedrooms samples (see Table A1 online). The number of single-person households is under-represented in the bedrooms sample, and so too, but to a lesser extent, is the percentage of under-occupied homes (see Table A2 online).

2.3 OVERHEATING ASSESSMENT

Initially, the bedroom temperature data were analysed using the well-established UK static 26°C/1% overheating criterion, which is based on a small number of measurements undertaken in 1975 (Humphreys 1979). This criterion classifies a room as overheated if there are > 1% of annual hours (i.e. > 32 hours) with a temperature > 26°C during the night (22:00–07:00 hours) (e.g. CIBSE 2017). However, this criterion classified 69% of the main bedrooms as overheated, a substantially higher prevalence than was reported by the EFUS households themselves.

Other researchers have also demonstrated that the static criterion produces a high estimate of the prevalence of night-time overheating (Mitchell & Natarajan 2019; Gupta et al. 2019; Morey et al. 2020; Gupta & Kapsali 2016; Pathan et al. 2017) and there are suggestions that night-time temperature tolerance is actually an adaptive process (Nicol & Humphreys 2018; Wyon et al. 1979). Here, therefore, as in the previous work by the present authors (Lomas et al. 2021), bedroom overheating is determined using an adaptive approach.

The adaptive thermal comfort theory (e.g. CIBSE 2013; Nicol et al. 2012) is based on the idea that people gradually adapt to higher temperatures and therefore that the temperature threshold, $T_{\text{max}}$, above which a space would be considered as too warm, increases with the ambient temperature, specifically with the running mean of the mean daily outdoor temperature $T_{\text{rm}}$. The value of $T_{\text{max}}$ is 1 K lower for ‘sensitive and fragile persons’ (Category I) than for people with ‘normal expectations’ (Category II). Variations of $T_{\text{rm}}$ with ambient temperature and of the Category I and II thresholds are illustrated in Figure 2. Figure 2a shows how changes in $T_{\text{rm}}$ lag behind the changes in daily temperature. During 2018, the largest $T_{\text{max}}$ at any of the EFUS homes was never more than 29°C (Category I) or 30°C (Category II).

In this work, households were classified as either Category I or II depending on the EFUS-vuln variable, which was derived from the household questionnaire. Thus, a household with members who were either aged 75 or over, or under five, or had long-term sickness or were registered disabled were classed as Category I, others were classified as Category II. Approximately 53% of the EFUS households were in Category I. Using this selected category (Sel.Cat) approach, the applicable threshold temperature, $T_{\text{max}}$, used in the analysis of night-time overheating differed from one household to the next.

When using adaptive criteria, the occurrence or not of overheating is based on the positive difference, $\Delta T$, between the room’s measured temperature and the relevant threshold ($T_{\text{max}}$). In this work, the overheating criterion given in UK guidelines (CIBSE 2013, 2017), which are based on international standards (BSI 2007, 2019), was used:
The number of hours \((H_e)\) during which \(\Delta T\) 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.

The occupied-hours were taken to be the nine hours from 22:00 to 07:00.\(^7\) Thus, 3% of occupied-hours between May and September (153 days) produces a limiting value for \(H_e\) of 41.5 hours. In 2018, high outdoor temperatures, which could lead to elevated temperatures, were recorded beginning in early May (Figure 2b).

### 2.4 IDENTIFYING SAFE HAVENS

The focus of this work is the protection from night-time overheating offered by safe havens. Therefore, the existence or not of safe havens was explored for the homes in which the main bedroom overheated as defined by the above criterion. In this work, either the living room or an alternative bedroom was considered as a potential safe haven. Throughout, terms such as ‘safe haven’ and ‘exposure to overheating’, etc., are only relevant to those who would otherwise sleep in an overheated main bedroom. This work does not attempt to shed light on the exposure to overheating, and the relief from it of others in the household.

The presence of safe havens was examined using two different definitions. The first, and simplest, was to define a room as offering a safe haven if it did not overheat at night based on the above criterion. If used for sleeping during the hot part of the year, those who would normally have occupied the main bedroom are thus protected from exposure to overheating.

A safe haven is a space in a dwelling with an overheated main bedroom which, if used for sleeping, prevents exposure to night-time overheating.

The dwelling temperatures shown in Figure 2b, for example, reveal a second bedroom that is invariably cooler than the main bedroom.

The second definition of a safe haven is based on the idea that on nights when the main bedroom is hot, i.e. the temperatures exceed the overheating threshold, the occupants sleep in a room which is cooler, i.e. has fewer hours over the threshold during the forthcoming night.\(^6\) Of course, on any given night, a cooler room may or may not exist. This definition therefore assumes that the people who would normally occupy the main bedroom switch rooms on a nightly basis, either between the main bedroom and the living room or between the main bedroom and an alternative bedroom, in order to sleep in the coolest space.\(^9\)

A safe haven is a space in a dwelling which if used on nights when the main bedroom is hot, prevents the exposure to night-time overheating.

As with the first definition, exposure to night-time overheating is defined by the adaptive criterion given above.\(^10\)

Switching rooms is the action recommended by the heatwave advice, but how do people know exactly when to sleep elsewhere? The room-switching definition used here presumes that people have perfect foresight, i.e. they know if a bedroom or the living room will be cooler than the main bedroom on the forthcoming night. The definition above thus provides the most optimistic estimate for the efficacy of the heatwave advice.

The prevalence of alternative bedrooms that offered a safe haven is calculated assuming that the cooler of the second or third bedrooms is unoccupied. However, an alternative bedroom may only be vacant in homes classed as under-occupied, i.e. that have a spare bedroom.\(^11\) In England, in 2017, roughly 37.1% of homes were classed as under-occupied (MHCLG 2019d), and the prevalence of under-occupancy was much greater in owner-occupied homes, 51.8%, than in privately rented homes, 13.7%, or in social rented accommodation, 8.5%.\(^12\) The total number of dwellings with bedrooms offering a safe haven is therefore also calculated assuming that they are only present in under-occupied homes. This will substantially reduce the estimated prevalence. Other factors that may reduce the real prevalence of safe havens are discussed below in Section 4.
Knowing the household composition (see Table A2 in the supplemental data online) and assuming that two people sleep in the main bedroom except in households with one person, it is also possible to estimate the number of people exposed to overheating, or relieved from such exposure by sleeping in another room.

The national prevalence of safe havens is measured by the percentage reduction in the number of English homes in which people are no longer exposed to night-time overheating. For example, a value of 33% implies that a safe haven can be found in a third of English dwellings with an overheated main bedroom.

The national benefit offered by safe havens is measured by the percentage reduction in the prevalence of English homes in which people are exposed to overheating by sleeping in a cooler room rather than an overheated main bedroom.

The percentage reduction is also a measure of the value of the heatwave advice to sleep in a cooler room. A value of 33% implying that the advice is effective for about one-third of households.

It is useful to know for which dwellings and for which sectors of society heatwave advice to sleep in a cooler room is relevant. It might be, for example, that the advice is useful for those living in large, under-occupied dwellings, but less useful for those living in smaller, fully occupied homes. Therefore, the prevalence of safe havens was disaggregated based on the category, and within each category the characteristics of the dwelling and household (see Tables A1 and A2 in the supplemental data online).

3. RESULTS

3.1 SAFE HAVENS AND THEIR EFFECTIVENESS

Before analysing nationally weighted results, it is instructive to examine the prevalence of overheating in the two individual samples and the frequency with which recorded temperatures exceeded the threshold temperature. The analysis is conducted on the presumption that people slept in the main bedroom unless an alternative room, either living room or bedroom, was cooler (second of the above definitions).

In the ‘living room sample’ of 553 homes, 431 did not have an overheated main bedroom (Figure 3a, yellow region). Of these, 282 (c65%) had one occupied-hour or less over the threshold temperature (0.1% of the 1377 occupied-hours between May and September). Of the 122 homes with main bedrooms that did overheat, four dwellings had main bedrooms that were chronically overheated, i.e. more than 50% of occupied-hours over the threshold. The hottest main bedroom exceeded the threshold temperature 91% of the time!

If people who normally slept in the main bedroom slept in the living room on nights when it was cooler, those in just 26 homes would remain exposed to overheating (Figure 3a, blue region), a reduction of 96 homes, or 79% (Figure 3a, pink region). In 41 of the homes people were exposed to temperatures over the threshold for just one hour or less between May and September.

In the sample of 553 as a whole, the mean reduction in the frequency of temperatures over the threshold (as a result of sleeping in a cooler living room) was 1.9 percentage points, the maximum reduction was 67 percentage points. In 41 of the 122 homes that had an overheated main bedroom (i.e. 33%), the frequency of temperatures over the threshold was reduced to one hour or less by sleeping in the cooler living room.

In the ‘bedroom sample’ of 308 homes, 226 did not have an overheated main bedroom (Figure 3b, yellow area). In the 82 homes that did have an overheated main bedroom, if people slept in a different, cooler bedroom, then those in 38 homes would be still exposed to overheating (Figure 3b, blue region), a reduction of 44 homes, or 55% (Figure 3b, pink region). In four of the homes people, were exposed to temperatures over the threshold for one hour or less as a result of sleeping in a cooler bedroom.
In the sample of 308 as a whole, the mean reduction in the frequency of temperatures over the threshold as a result of sleeping in a cooler bedroom was 1.0 percentage points; the maximum reduction was 12 percentage points.

The analysis of the samples suggests that if living rooms, rather than alternative bedrooms, are used as a safe haven, by those who would otherwise sleep in the main bedroom, there is a greater reduction in exposure to night-time overheating and a much greater reduction in exposure to hot conditions.

3.2 NATIONAL PREVALENCE OF SAFE HAVENS

The national prevalence of overheating in the main bedroom, living room and an alternative bedroom (in homes where these exist) is calculated using the two weighted samples. The reduction in the prevalence of overheating due to sleeping in either the living room or an alternative bedroom, i.e. the prevalence of safe havens, is then calculated. The prevalence of safe havens in the different categories of dwellings and households is also explored. For the data underlying the analyses and the results, see Tables A3, B1, B2 and B3 in the supplemental data online.

3.2.1 Prevalence of overheating in different rooms

The national prevalence of overheating in the main bedrooms deduced from the sample of 553 homes is 18.6%, 4.45 million homes, (see Table A3 in supplemental data online), which is very similar to the value previously reported, 19% (Lomas et al. 2021). Thus, approximately 7.4 million people, around 19.5% of all English people who sleep in a main bedroom, were exposed to overheating. In the 34.3% of homes that were under-occupied, the prevalence of overheated main bedrooms was 10.1% and in fully occupied homes, 23% (see Table B1 in the supplemental data online). Therefore, fewer people living in under-occupied homes will need to consider seeking out, and sleeping in, a safe haven compared with those living in fully occupied homes.

Just 8.0% of the English stock (1.91 million dwellings) had living rooms that overheated at night, which is 57% less than those with overheated main bedrooms (Figure 4). In under-occupied homes (Table B1 in the supplemental data online) the prevalence of night-time overheating in the living rooms was just 3.9%. These figures are much lower than the prevalence of daytime overheating in living rooms, 15% (Lomas et al. 2021).

In the homes where a second or third bedroom was monitored (sample size of 283), the prevalence of overheating in the coolest bedroom was only 7.1% less than in the main bedroom (Figure 4). In under-occupied homes the prevalence was 12.0% less than in the main bedroom.
These results suggest that living rooms may provide a safe haven in many homes, but that the prospects of finding a safe haven in another bedroom are much more limited. However, homes with an overheated main bedroom may not be those in which the second or third bedroom overheats and, on any particular night, one or other of the alternative bedrooms might be cooler than the main bedroom. The prevalence of alternative bedrooms as a safe haven is thus worthy of further investigation.

3.2.2 Sleeping in a different room

If people with overheated main bedrooms slept in the living room throughout the warm part of the year (May–September) the national prevalence of night-time overheating would be just 4.7% (1.135 million homes). Thus, living rooms provide a safe haven in 74.5% of English homes that had an overheated main bedroom (see Table B2 in the supplemental data online). If it were only practical for people in under-occupied homes to sleep in the living room, then safe havens would be found in just 15.4% of homes with an overheated main bedroom (Figure 5a).
If, during the warm part of the year, those living in homes with more than one bedroom were to sleep in the cooler of the second or third bedrooms rather than the overheated main bedroom, then the prevalence of overheating would be reduced by 34.4%, i.e. alternative bedrooms provide a safe haven in 34.4% of homes (see Table B2 in the supplemental data online). However, the ability to shift rooms may only be available to those living in under-occupied homes, in which case safe havens are to be found in just 6.6% of homes with an overheated main bedroom (Figure 5a).

Clearly living rooms, whether available for sleeping in all homes or only in under-occupied homes, are much more likely to offer a safe haven than an alternative bedroom.

3.2.3 Switching nightly to sleep in a cooler room

If, during the warm period of the year, people switched nightly between the main bedroom and the living room to sleep in whichever is the cooler, the prevalence of night-time overheating would be 4.4% (1.051 million homes). Thus, safe havens would be found in 76.4% of homes with an overheated main bedroom (Figure 5b, and see Table B3 in the supplemental data online). This would benefit around 5.8 million people, 79% of those who sleep in an overheated bedroom. If only under-occupied homes had living rooms available for sleeping, then the prevalence of safe havens would be just 16.0%.

Switching nightly to sleep in the coolest of the main bedroom or an alternative bedroom, should one exist, would provide a safe haven in 46.7% of homes (see Table B3 in the supplemental data online). This would relieve approximately 51% people from exposure to overheating. If only those in under-occupied homes could sleep in an alternative bedroom, rather than the overheated main bedroom, then the national prevalence of safe havens would be just 9.0% (Figure 5b). Clearly alternative bedrooms are less likely than living rooms to provide a safe haven.

Overall, the nightly switching of the place of sleeping has little impact on the prevalence of safe havens compared with simply sleeping in either the living room or the coolest alternative bedroom on every night during the warm season.

3.2.4 Influence of dwelling and household characteristics on prevalence of safe havens

The influence of dwelling and household characteristics on the prevalence of safe havens, if occupants switch rooms nightly, was examined. For the results for all the dwelling and household categories analysed, see this paper's supplemental data online. Here only the dwelling or household characteristic that had a significant impact on the prevalence of safe havens, as identified by a Chi-squared test ($p < 0.01$), are discussed (see Table A3 in the supplemental data online).

There was no significant difference at the 1% level ($p < 0.01$) in the prevalence of safe havens as a result of switching bedrooms for any of the dwelling or household characteristics. At the 5% level ($p < 0.05$), alternative bedrooms provided a safe haven in fewer flats than in other dwelling types. In contrast, the percentage of English homes offering a safe haven, if people switched nightly between the overheated main bedroom and the living room, was significantly influenced by ($p < 0.01$) dwelling type, floor area and the number of persons in the household.

There were significantly fewer safe havens to be found in flats and bungalow, 29.6%, than in detached and semi-detached dwellings (Figure 6). Significantly fewer homes with a floor area less than 50 m$^2$ provided a safe haven, 14.6%, compared with dwellings with a larger floor area, 77.5–93.4% (Figure 7). In single-person households, the prevalence of safe havens was significantly less, 49.1%, than in households with more members, 84.3% (see Table A3 in the supplemental data online).

Overall, these results suggest that those living in small dwellings, which are often flats, and which, compared with other dwelling types, are more often the home of one person, are significantly less likely to have a living room that provides a safe haven.
4. DISCUSSION

This work clearly shows that, except in bungalows, flats and other small dwellings, living rooms are more likely to provide a safe haven than spare bedrooms. Furthermore, the frequency of exposure to hot conditions, i.e. temperatures above the adaptive comfort threshold, is much less if the living room is used as a safe haven rather than a bedroom.

The greater variation of living room temperatures than bedroom temperatures with dwelling characteristics, and thus the greater variation in the prevalence of safe havens offered by living rooms, is in line with previous results (Lomas et al. 2021). The greater temperature variation is to be expected because, compared with bedrooms, living rooms are more often on the ground floor of two (or more) storey houses and so are shaded by the surrounding environment and are perhaps more thermally heavyweight, with solid floor and structural walls. Also, warm air generated during the day will tend to rise to the bedroom spaces above with cool, dense night air, which is admitted to provide ventilation, pooling on the ground floor. In flats and bungalows, 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 effects driving living room and bedrooms temperatures.
Because rooms on lower floors are likely to be cooler at night, if climate-resilient dwelling design were to be considered, it would seem sensible to consider providing cool rooms on lower floors. Passive cooling would be more likely to succeed, and if mechanical cooling were needed, the energy demand would be less. Work by Palmer et al. (2014) in an Australian context indicated that these strategies can be successful. Traditions in English dwelling design together with established patterns of sleeping, and other concerns such as security, noise, etc., may, however, act against such a strategy.

Previous studies have highlighted that people generally prefer lower temperatures in bedrooms (Peeters et al. 2009; Berge & Mathisen 2016) and choosing to sleep in another, cooler, bedroom during spells of hot weather is an identified adaptive behaviour (Wright et al. 2018). But people are not machines. The ways in which people use their home will be stochastic rather than precise (Nicol & Roaf 2007). So, although it may be challenging to determine a specific temperature threshold at which people might choose to sleep in another room, there will be a greater probability that they will do so as the temperature rises (Nicol & Roaf 2007).

The estimates of the reductions in exposure to high night-time temperatures and the prevalence of safe havens represent a best possible scenario. First, it is presumed that the living room or alternative bedrooms can be moved into even though in many homes this might not be the case, because: the alternative bedroom is already occupied by other members of the household; although ‘called’ a bedroom the room is actually furnished for other purposes, e.g. as a study or a hobby room; living rooms may not have a sofa or other space for sleeping; or the room is unsuitable for sleeping because of ambient noise, security concerns or other factors. Second, the number of flats, which tend not to have safe havens, is under-represented in the data samples used in this research. Third, people may not be able to move bedroom, in particular the elderly, infirmed or ill, who require physical and medical support which has been set up in the main bedroom. Fourth, the analysis only sheds light on the benefits of night-time room-shifting for the occupant(s) of the main bedroom, yet other bedrooms also overheat perhaps more so than the main bedroom. Fifth, of course, the simple act of sleeping in a different space, in a different ‘bed’, with different ambient sound and light, can disrupt sleep. There will, therefore, be an inevitably reluctance to shift rooms, even on hot nights. Finally, although the highest estimated reductions in exposure to overheating presume that the occupants of the main bedroom have a ‘crystal ball’ which tells them if the living room, or an alternative bedroom, will be cooler in the forthcoming night, it may be that the living room or, as illustrated in Figure 2, an alternative bedroom, is invariably cooler than the main bedroom and could become the preferred place for summertime sleeping. For all these reasons, the prevalence of practically useable safe havens is likely to be much less than the most optimistic values quoted herein. Perhaps the calculated prevalence of safe havens assuming that they can only to be found in under-occupied dwellings is more realistic.

In this work, the adaptive thermal comfort thresholds derived for living spaces have been used to assess bedrooms. Although evidence is accumulating to suggest that attaining comfort for sleep, and retaining it during sleep, is an adaptive process (e.g. Nicol & Humphreys 2018; Wyon et al. 1979), appropriate threshold temperatures and their allowable maximum value, the rate of change of threshold temperatures and the parameters that drive this change, etc., are far from clear. Much work remains to be done in this area.

Although adaptive comfort models have gained widespread use in overheating assessments for residential buildings (de Dear et al. 2020), there is still uncertainty as to whether the range of temperatures that is ‘acceptable’ to a person from a comfort point of view will affect their health (Kenny et al. 2019). This leads to a certain disjunction between epidemiological research, which generally uses air temperature or heat index as an exposure indicator, and built environment research, which typically adopts a percentage of hours above certain thresholds and a pass/fail criterion (Zuurbier et al. 2021). Considering the need to adapt existing English homes against the effects of climate change, it will be important to establish whether there is a desire to maintain thermal comfort at all times, allow for a certain level of discomfort without heat-related health effects, or to prevent heat-related health outcomes. The analysis and dwelling design strategies to achieve each of these may be quite different.
This research and previous research by the present authors and many others indicate that advice to households about how to stay safe during heatwaves could be much more focused. A recent review of England’s heatwave plan by Williams et al. (2019b) makes the same point. There is a need for more targeted advice aimed at different population groups living in different settings, and a need to increase knowledge of the effectiveness of heat-protective behaviours. Identifying if one’s home has a safe haven, and being prepared to sleep in it during hot weather, aligns with these suggestions.

There are some limitations in this study. First, there is a peculiarity in the analysis because the threshold temperature (used in the adaptive criterion) is based on the mean daily temperature and so changes at midnight. Alternative approaches in which the threshold temperature is held constant through the night are not thought to have much impact on the calculated percentage reductions in night-time overheating. However, the assessment of night-time overheating might require a different approach to determining a running mean temperature (or similar metric). In the EFUS data set, the second and third bedroom temperatures were only available for some homes, those where the household gave permission for monitoring and where the data were reliable. The sample of homes is thus diminished, and it is unknown whether the sample of homes is biased. The size of the samples is especially limiting when only the homes with overheated main bedrooms are disaggregated by dwelling and household characteristics. The samples analysed also had an under-representation of flats and bungalows, even after weighting, which also suggests that the calculated prevalence of safe havens is optimistic. Future surveys should strive to measure temperatures in all bedrooms.

Finally, and most importantly, this work offers no insight into the temperatures that would result in people considering moving room, their willingness actually to do it or their subsequent sleep quality which, as noted above, could be degraded for many reasons unrelated to temperature. The practicality of bedroom-shifting for society’s most vulnerable, the disabled, ill and cared for, may be particularly limited. Thus, whilst this work provides evidence that safe havens exist, further work, which includes summertime surveys of the opportunity and willingness to move rooms, is needed.

5. CONCLUSIONS

The prevalence of night-time overheating in the main bedrooms of homes during England’s hottest summer in 2018 has been determined using data collected as part of the Energy Follow Up Survey (EFUS) to the English Housing Survey (EHS). The data set also includes temperatures measured in the living rooms and in other bedrooms. The prevalence of night-time overheating in these rooms during the warm part of the year (May–September) was determined using an adaptive thermal comfort overheating criterion.

The national benefit of safe havens is measured by the percentage reduction in the prevalence of English homes in which people are exposed to overheating by sleeping in a cooler room rather than in an overheated main bedroom. The prevalence of safe havens in the English stock provided by (sleeping in) living rooms or an alternative bedroom is calculated. The calculations provide an upper bound; there are many reasons why, in practice, alternative rooms may not make a satisfactory safe haven for sleeping.

The main bedroom overheated in 4.4 million homes (18.6%) in England, which exposed around 7.4 million people to overheating. The prevalence of night-time overheating in living rooms was 57% less, but the prevalence of overheating in alternative bedrooms was only 7% less. The differing thermal characteristics of these room types can explain these results.

If people switched nightly to sleep in the cooler of the main bedroom or living room, the prevalence of night-time overheating would be just 4.4% (1.051 million homes). Thus, safe havens are to be found in 76.4% of English homes with an overheated main bedroom, which would benefit around 5.8 million people.

Switching nightly to sleep in the cooler of the main bedroom or an alternative bedroom would provide a safe haven in 46.7% of homes with an overheated main bedroom. This would
relieve approximately 51% of the people with an overheated main bedroom from exposure to overheating. If only those in under-occupied homes had an alternative bedroom in which to sleep, the prevalence of safe havens would be just 9.0%.

Dwelling and household characteristics had a significant influence ($p < 0.01$) on the prevalence of living rooms as a safe haven, but not alternative bedrooms. Significantly fewer safe havens were to be found in the living rooms of flats and bungalow, 29.6%, than in detached and semi-detached dwellings, and significantly fewer homes with a floor area less than 50 m$^2$ provided a safe haven, 14.6%, compared with dwellings with a larger floor area. In single-person households the prevalence of safe havens was significantly less, 49.1%, than in multi-person households. Thus, it is dwellings that are more likely to have an overheated main bedroom in which safe havens are less likely to be found.

Public health advice, especially during heatwaves, should be tailored to the characteristics of dwellings and households, and could usefully emphasise the benefits of sleeping in the living room, where possible, on hot nights.

The pressure to air-condition English homes is alleviated if people sleep in safe havens or cool rooms. These are these more likely to be found on the lower floors of English homes, which frequently includes the living room.

Further socio-technical research is needed to understand fully the number of people exposed to summertime overheating. Future field studies should diligently measure temperatures in all bedrooms, and household surveys could identify the practicality of capitalising on any safe havens that do exist.

NOTES

1 In this paper, homes refer to occupied dwellings. Dwellings may be houses or flats (apartments). Examples of the common UK dwelling categories, as used in this research, are shown in Figure 1. End-of-terrace dwellings, although having three walls exposed, are combined with mid-terrace dwellings in all analyses.

2 From 1 October 2021, the PHE’s health protection functions were transferred into the UK Health Security Agency.

3 Researchers often agonise over precisely what temperature loggers are recording. Many, perhaps without thinking, simply state air temperature. In fact, as noted by Lomas & Porritt (2017: 6):

   it is very likely all the sensors used record some (undefined) mix of air and radiant temperature with, possibly, a component of surface temperature (conduction from the mounting surface). [...] In occupied spaces it is practically difficult to measure pure dry-bulb or mean radiant temperature [...] therefore, and rather conveniently, sensors might record a temperature closer to that sensed by occupants than the dry-bulb temperature.

4 Solar radiation impinging on sensors, local heat sources, sensors being stored away or being moved around the room or from room to room are all causes of unreliable temperature traces.

5 This second sample of 283 homes thus represents a reduction of 308 homes compared with the parent sample of 591, which is much greater reduction than the 10–15% of English homes (ONS 2021) thought to have only one bedroom. This suggests that in many of the EFUS homes with more than one bedroom the temperatures were not measured.

6 The questionnaire delivered to around 2500 EFUS households following the summer of 2017 revealed that 17% thought that their bedroom was either sometimes or often uncomfortably warm. Although cooler than the summer of 2018, the value is a quarter of the prevalence that the static criterion generated (69%).

7 Using the EFUS temperature data, the value of $\Delta T$ was calculated at each half-hour between 22:30 and 07:00 hours. The calculated half hours $< T_{max}$ were then halved to produce the hourly percentage exceedance. The period 22:30–07:00 hours is thus the assumed occupancy period,
which, of course, may not represent the actual period for which a bedroom is occupied on any given night.

8 The number of half-hours over the threshold temperature in the living room during the night (22:30–07:00 hours) was compared with the number of night-time half-hours over the threshold in the main bedroom. For bedrooms as a safe haven, the same approach is used, but comparing the half-hours in the coolest bedroom.

9 Of course, this approach presumes that people have perfect foresight and so produces the best possible benefit that room-changing might have.

10 The total night-time hours between May and September with a temperature over the threshold, whether measured in the main bedroom or, if it is cooler, in the living room, was used to establish if the occupants had or had not been exposed overheating (limiting value 41.5 hours). The same analysis was used to test if sleeping in an alternative bedroom would, or would not, result in exposure to overheating.

11 Households are said to be under-occupying their property if they have two or more bedrooms more than the notional number needed according to the bedroom standard definition (MHCLG 2019d: 43).

12 In the weighted sample of 553 homes, 34% were under-occupied, and in the weighted sample of 308, it was 30%.

13 Some homes in the sample do not have alternative bedrooms. The data points of these homes lie on the equality line in Figure 5b.

14 After weighting, the prevalence of overheating in main bedrooms generated by the small sample of 308 was 23%, which is greater than for the sample. The prevalence of overheating in the main bedroom of the sample of 283 homes after national weighting was 23.4%, which is very similar to the prevalence deduced from the seeded nationally weighted sample of 308 rooms, 23%. However, these differences are largely overcome when estimating the national prevalence of safe havens because this is expressed as a percentage reduction in the overheating in the main bedroom for the same sample.

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AUTHOR CONTRIBUTIONS

The initial analysis, and the first report, which explored the potential of the Energy Follow Up Survey (EFUS) data set for identifying safe havens, was undertaken by P.D. S.W. undertook the more refined analysis and investigated the influence of dwelling and household characteristics. K.J.L. was responsible for securing access to the data, managing the work and the production of the latter versions of this paper.
COMPETING INTERESTS
The authors have no competing interests to declare.

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