Overheating in buildings: lessons from research

Kevin J. Lomas and Stephen M. Porritt

School of Civil and Building Engineering, Loughborough University, Loughborough, UK

Introduction

There is growing evidence of an increased incidence of overheating during warm weather in buildings without air-conditioning, especially homes in temperate climates where the retention of winter heat has been the principal focus of thermal design. Overheating has been particularly notable in new homes and in existing stocks. Excess heat affects the health and wellbeing of occupants, especially if sleep is degraded. In extremis, the heat stress caused can lead to premature mortality, especially amongst more vulnerable members of society. The problem came vividly to the fore during the devastating 2003 pan-European heatwave which caused 15,000 premature deaths (PHE, 2015).

In territories where air-conditioning is already used, or even essential to maintain comfort, there is an interest in the indoor temperatures that might occur should the mechanical cooling equipment or the electricity supply fail. The concern here is survivability in relatively rare and unpredictable circumstances.

This special issue presents overheating studies by 12 groups of researchers. The papers, which were selected from the 79 submitted abstracts, describe work conducted in Australia, China, Germany, India, New Zealand and the UK (Table 1). They describe monitoring campaigns in occupied buildings, modelling studies, controlled trials in full-size test buildings and laboratory experiments, in short, the full range of approaches that might be used to shed a light on the incidence of overheating, the causes of it, and the impact on and response of building occupants.

This editorial places these papers in context and compares and contrasts the research findings; it is shaped by the consideration of six questions:

- Why is overheating a problem and why now?
- When is a building overheated?
- How do people respond to heat?
- How widespread is overheating?
- Can we predict overheating?
- What should we do next?

The chosen papers contain an excellent array of references to the extant literature[1], which makes this issue a valuable resource for those new to the field, and obviates the need for an extensive background review here.

Table 1 here. Articles in this special issue 'Overheating in Buildings: Adaptation Responses', Building Research & Information (2017)

[1] These are a valuable adjunct to the list of overheating literature already compiled by Building Research & Information. Also relevant are two special issues 'Counting the Costs of Comfort' (2015), 43(3) and 'Adaptive Comfort in an Unpredictable World' (2013), 42(3).

Why is overheating a problem and why now?

Overheating has been observed across Europe and in North America (e.g., Lane et al., 2014; Lee & Shaman, 2016), but in this issue the majority of the papers, eight in all, are from UK researchers, which is illustrative of the rising level of concern about overheating in many places with a temperate climate. Seven papers report monitoring studies conducted between 2009 and 2015 in dwellings covering the entire nation. They report primary data collection and an analysis of secondary data from the English survey of over 800 dwellings (DECC, 2013). The primary studies vary in scale, with data collected from between 101 and 18 homes, and temperatures typically recorded in the main bedroom and living room (Table 2). Overheating is shown to occur in dwellings stretching from the south-east and south-west of England to the north of Scotland. The papers give insight into the incidence and causes and effects of overheating which will be of interest to policy-makers, designers, housing authorities, researchers, etc. in many countries.

Table 2 here. Summary of the monitoring studies in domestic UK buildings.

Why, though, should overheating be a particular problem in European homes and in the UK in particular, and why now? After all, the UK is a small, if densely populated, island with relatively mild winter weather and temperate summer conditions. Situated off mainland Europe between 50 and 59°N, the ambient temperature in the warmest part, London, has exceeded 26.1°C for less than 1% of the time in the last 30 years (CIBSE, 2015), so domestic air-conditioning is very uncommon. But rather counterintuitively, it is this benign climate, together with the prevailing economic, political and cultural context, that has laid the foundation for the current overheating problem.

The mild UK climate has precipitated buildings that are relatively poorly insulated. Largely spared from wartime destruction, and protected by heritage considerations, the housing stock is one of the oldest in Europe (CLG, 2007), and it evolves very slowly. The traditional un-refurbished homes do not therefore retain heat well and so overheating has not historically been a concern. The building regulations, which evolved to ensure homes were safe and healthy, have, since 1965, sought to reduce heat loss in cold weather by setting minimum standards for the thermal envelope. Ventilation is prescribed to ensure adequate background ventilation and enable the rapid purging of indoor pollutants. Windows are designed to ensure adequate natural light. There is no regulatory consideration for design to control overheating in warm weather.

Across the world, concerns about climate change and energy security have, in the last two decades, led to vigorous policies attempting to improve the energy efficiency of housing stocks. New homes are increasingly efficient (e.g., HMG, 2016a) with the Passivhaus concept (Hopfe & McLeod, 2015) being an embodiment of such heat-retentive design. Policies and regulations to upgrade existing buildings have also been enacted in many countries (e.g., HMG, 2016b). In the UK the combined effect has been to reduce the average heat loss of the housing stock (circa 27.6 million homes in 2013) by 23% since 1970 (Palmer & Cooper, 2013)[2]. Whilst the insulation standard of existing homes is improved, and unwanted air infiltration reduced, virtually no consideration is given to summertime heat gains. Furthermore, extensions, conservatories, new window systems and other adaptations all conspire to reduce the prospects for adequate ventilation and increase the risk of summertime overheating. Whilst the potential for exacerbating overheating risk is now recognized (DECC, 2015; Porritt, Cropper, Shao, & Goodier, 2013), the matter is paid little attention in practice.

In places with cold winters, health and welfare concerns continue to focus attention on heat retention rather than summertime comfort. For example, more than 10% of England's households were classed as being in fuel poverty in 2014 (DECC, 2016)[3] and excess mortality due to low indoor winter

[2] From an estimated 376W/K in 1970 to 290W/K in the current stock homes. Of the UK dwellings suitable for each efficiency measure, 87% have double-glazing, 47% have over 150 mm of loft insulation and 64% have cavity-wall insulation (Palmer & Cooper, 2013).

[3] Fuel poverty in England is measured using the low income-high costs indicator, which considers a household to be fuel poor if they have required fuel costs that are above average (the national median level), and if they to spend that amount, they would be left with a residual income below the official poverty line (DECC, 2016).

temperatures in England and Wales was 43,900 in 2014/15. By comparison, summer heat mortality is an order of magnitude less. For example, during the 10-day European heatwave of 2003, there were over 2000 excess deaths in England[4], and during the heatwaves of 2006 and 2009 there were about 680 and 300 excess deaths, respectively (PHE, 2015)[5]. As the climate warms, however, the picture will change. By 2040 the temperatures experienced in the UK in the summer of 2003 will be the norm (PHE, 2015), and heat-related deaths could treble by the 2050s due to climate change (ZCH, 2015). Whilst protection from winter cold remains a priority, concerns about summertime health will escalate, and adaptation of buildings will be necessary (e.g., CCC, 2014).

The construction industry is always concerned about reducing cost, increasing the speed of construction and minimizing risk. Increasingly, therefore, dwellings are composed of standardized, performance-guaranteed components, delivered to site by road. Transport costs, site-handling considerations and resource efficiency mean that construction materials are becoming increasingly lightweight. This is especially so when so-called ‘modern methods of construction’ are employed, in which walls and other components or even entire rooms might be created off-site. Such methods lead to compact dwellings, and walls made of thermally lightweight materials, thin metal, wood, plastic and plasterboard. Thus, they lack the thermal mass necessary to ameliorate the large temperature swings caused by summertime internal and solar gains. In concert with good insulation standards, this lack of thermal mass renders such buildings more susceptible to summertime overheating (NHBC, 2012).

Urbanization, restrictions on building on rural land and high land prices have led to an increase in high rise apartment buildings and the use of rapid construction methods to reduce the time spent working in cramped urban settings. Such apartments tend to have lower ceilings and are often single aspect, preventing cross-ventilation. The buildings may have large windows to create a modern ‘glassy’ appearance. These can be heavy and difficult to open; with security concerns and traffic noise often mitigating against a willingness to do so. Night-time ventilation, which could do much to alleviate overheating risk, is especially curtailed by urban noise. Mechanical ventilation systems are often installed to overcome these problems and to recover heat from exhaust air in winter. In many countries, however, knowledge about how to install such systems is poor and they fail to perform well (Brown & Gorgolewski, 2015; McLeod & Swainson, 2016). The tendency of urban apartments to overheat (GHA, 2014) is further exacerbated by the inherently higher ambient temperatures in summer, and particularly summer nights, caused by the urban heat island, and the high internal heat gains, as hot water is permanently pumped around from central boiler plant.

Given the inherent climate of northern Europe and North America, in most places there is not a culture of designing and operating buildings to cope with summer heat. Thus, people are resistant to changes to the aesthetic of the homes and other buildings they occupy. External shading devices[6], shutters, green roofs, etc. may therefore be resisted by house buyers. Consequently, developers and house builders have no buyer incentive or, as noted above, regulatory requirement to provide heat protection. It would also add to construction costs, construction time and design complexity. However, built environment professionals understand they have an implicit duty of care to the occupants of buildings and so there is a concern whether buildings created now will still be fit for purpose in the years ahead.

The people who occupy dwellings, their susceptibility to elevated temperatures and the way they behave have a significant impact on the actual incidence of overheating. The elderly are especially vulnerable. They are less sensitive to ambient conditions and physiologically less able to regulate their body temperatures, which can be exacerbated by medication that further reduces physiological tolerance. Respiratory illness or cardiovascular disease can mean that the effects of high temperatures are much more serious. The elderly also tend to suffer from physical impairment, such as arthritis and

[4] Compared with the average over the same period during the previous five years.
[5] Compared with similar periods in previous years.
[6] External shading devices are of course the cultural norm across Europe and so visually accepted. They are standard practice in France, for example. The UK now experiences temperatures in summer similar to those previously encounter in central France and by 2080 will experience conditions similar to those in the south of France. The ubiquitous tendency for UK windows to open outwards also mitigates against external stutters, especially as a retrofit measure.

reduced mobility, which can make it difficult to move around (to escape the heat) and operate windows, trickle vents and other devices. Cognitive impairment, also more likely in the elderly, inhibits decision-making and is a barrier to learning, e.g., learning when is the optimal time to open windows or how to use a new mechanical ventilation system effectively. Because we are living longer, the proportion of populations comprised of elderly people is increasing rapidly[7]. These, and other factors mean that the elderly are at far greater risk during hot weather spells than other sectors of society and they are a sector that is increasing in number (PHE, 2015).

It is worth noting that the emergence of small, low cost, low-power but reliable temperature sensors in the mid-2000s has made feasible large-scale monitoring campaigns that last many months. In concert with the storage capacity of modern laptops and easy-to-use statistical software, these campaigns have exposed the scale and extent of the overheating problem and have started to shed a light on which people, in which homes in which locations are most at risk. The reviews in the papers in this issue provide this background literature, but the following works are particularly notable (Armstrong et al., 2011; Beizaee, Lomas, & Firth, 2013; Lomas & Kane, 2013; Mavrogianni, Wilkinson, Davies, Biddulph, & Oikonomou, 2012, and associated works; Mavrogianni, Taylor, Davies, Thoua, & Kolm-Murray, 2015; Porritt et al., 2013, and related works; Taylor et al., 2014, and later works; and Hajat, Kovats, & Lachowycz, 2007, and later works).

The foregoing discussion has highlighted how the energy-efficient refurbishment of existing housing stocks, the building of new well-insulated buildings, especially using thermally light-weight methods, together with the noticeably warmer climate compounded in some areas by the urban heat island, can shift housing stocks into territory in which it ceases to function well and for which occupants are culturally unprepared. As a result, UK homes are now increasingly experiencing summertime overheating. The UK is not alone in experiencing this phenomenon, but drivers will vary according to specific conditions in each country.

When is a building overheated?

At present there is no robust, defensible and universally accepted definition of overheating either for use in the assessment of proposed dwellings, for example, by modelling, or for as-built evaluation. Gupta et al. in this issue provide a useful listing of some overheating criteria commonly used in the UK. However, it is the evaluation of existing, occupied dwellings that is most troublesome. Consequently, the papers reporting monitoring studies use different criteria to evaluate whether or not overheating has occurred. The differences lie in both the substantive criteria chosen as well as the detailed application. The problems arise because of the way criteria have evolved.

Overheating criteria were developed in the late 1980s for use by modellers and different countries used different criteria (for a summary, see, for example, Cohen, Munro and Ruyssevelt, 1993). The criteria were specified in association with the weather data that were to be used in the model for making the overheating assessment; in the UK, the Chartered Institution of Building Services Engineers (CIBSE) developed design summer years for this purpose (CIBSE, 2002) and it continues to update them (CIBSE, 2016). The criteria evolved over time, but were essentially static in nature, i.e., the threshold temperatures above which overheating is deemed to occur do not change with the ambient temperature (Figure 1). The criteria used for assessing proposed Passivhaus designs are also static (Figure 1). The central point here is that the criteria were evolved for use by modellers at the design stage of buildings; it is their application for assessing buildings in use that is problematic.

With the introduction of adaptive thermal comfort methods (ANSI/ASHRAE, 2013; British Standard EN15251, 2007), the applicable overheating criterion and the weather data become inexorably bound up. The temperature thresholds increase with the running mean of the ambient temperature and the

[7] In the UK the number over 65 years will have increased by 40% by 2032. By 2040, almost 25% of the UK population will aged be over 65 (AgeUK, 2016).

Figure 1. Thermal comfort and overheating criteria. Adapted from Lomas and Giridharan (2012) to show static criteria and the effect of a ceiling fan.

thermal sensitivity of the occupants determines which (increasing) threshold is used (Figure 1). These adaptive thermal comfort standards are offered for use at both the design stage and for the assessment of buildings in use. Nevertheless there are still difficulties associated with their application to occupied buildings, particularly in relation to bedrooms and sleep quality.

Five papers in this issue adopt the Passivhaus Planning Package (PHPP) criteria or the CIBSE criteria; McGill et al. use both (Table 2). Morgan et al. and McGill et al. apply an approximate form of the PHPP criteria, which is that temperatures during annual occupied hours should not exceed 25°C for more than 10% of the time (Passivhaus Institut, 2012)[8], the exceedance of which determines whether or not the Passivhaus compliance has been demonstrated (by the monthly calculation tool). In the PHPP the house is modelled as a single zone. McGill et al., Baborska-Narożny et al., Vellei et al. and Gupta et al. apply approximate versions of the CIBSE static criteria, which is that no more than 1% of annual occupied hours over an operative temperature of 28°C, or, in bedrooms, no more than 1% of annual occupied hours over an operative temperature 26°C (CIBSE, 2015). McGill et al. also use the CIBSE originated 5%/25°C criterion (CIBSE, 2006).

All the papers struggle to apply the criteria precisely. First, it is difficult to gather an unbroken stream of data for a whole year and so the criteria are applied to part of the year only, typically a summertime period. Taken to the extreme, it would invariably be possible to find a brief period of high indoor temperature with more than 1% of hours over the threshold. Second, it is difficult to determine the occupied hours, although Baborska-Narożny et al. put effort into doing this. Most authors make a reasonable assumption about likely hours of space occupancy. These difficulties do not arise of course when the criteria are used in association with modelling. More generally, some authors apologize for recording dry-bulb temperature rather than operative temperature. In fact, 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). Many authors implicitly recognize this when stating that the sensors were mounted away from heat sources and out of direct sunlight. In occupied spaces it is practically difficult to measure pure dry-bulb or mean radiant temperature. In fact therefore, and rather conveniently, sensors might record a temperature closer to that sensed by occupants than the dry-bulb temperature.

Four of the papers use the more recently published CIBSE TM52 three-criterion system (CIBSE, 2013), whereby two of the following three must be breached for overheating to have occurred:

- Criterion 1: No more than 3% of the occupied hours during the non-heating season should be more than 1 K over the adaptive comfort threshold defined in BS EN 15251. The CIBSE guide says the non-heating season is typically 1 May–30 September (153 days).
- Criterion 2: The exceedance of the chosen threshold on any one day should be less than 6 degree-hours (K.hr).
- Criterion 3: There must be no single occupied hour more than 4 K over the threshold. Criteria 2 and 3 are not constrained to the summer period.

The threshold, which is based on the operative temperature, can be tightly specified, i.e., Category I (vulnerable households) or more relaxed, 1K higher (Category II, non-vulnerable), or 1K higher still (Category III). The threshold increases with the running mean of ambient temperature to reflect the

[8] The PHPP actually has a range of criteria: exceedance of 25°C more than 15% of the time is termed Catastrophic; 10–15%, Poor; 5–10%, Acceptable; 2–5%, Good; and 0– 2%, Excellent.

adaptation of people as ambient temperatures rise and fall (Figure 1). The CIBSE Guide A (2015) and the standard BS EN 15251 explicitly state that the assessment applies to both modelling and as-built assessments.

The whole TM52 criterion set is given above to illustrate the complexity. For strict application, data are needed over both the summer period (Criterion 1) only and the whole year (Criteria 2 and 3) and occupied periods must still be determined or assumed. The application also requires the external ambient temperature to be recorded. Some researchers use the nearest weather station, which may be some kilometres away, whilst others, such as Mavrogianni et al. and Gupta et al., set up (a) dedicated logging station(s). There is also the need to choose whether occupants are sensitive (Category I) or not (Categories II or III).

Some commentators feel that the TM52 criteria should not be applied to bedrooms, where sleep disruption rather than thermal comfort is the principal concern. (The TM52 criteria were devised primarily from field studies of office workers.) Thus, the Zero-Carbon Hub, a UK non-profit organization advising on zero-carbon homes policy, suggest that the fixed 1%/26°C criterion should be used for bedrooms, on the basis that adaptive opportunity is limited and cannot in any case be exercised without sleep disruption (ZCH, 2016). The present lead author is unconvinced by this argument, not least because people are quite adept at setting the ventilation of bedrooms and choice of bed wear and bed covers at the start of the night[9] and, almost without noticing, will move a duvet or blanket to expose more or less body and fine tune exposure through the night. It is also the case that the evidence base for the 26°C criterion is thin. The adaptive opportunity might be more limited at night but it is not zero and adaptive opportunity can be exercised without unduly disrupting sleep. Thinking long-term, it is known that people from warmer climates can sleep soundly in bedrooms that others, used to cooler night temperatures, would find too warm. Therefore, it is reasonable to assume that climatic warming will precipitate adaptation to warmer nights. The question of night-time thermal comfort is in need of research, but it would be ethically difficult and hard to retain ecological validity.

The CIBSE Guide A (2015) acknowledges that there are difficulties with the in-use application of the overheating criteria, stating that ‘The measurement period for all measured parameters should be long enough to be representative, for example 10 days’ and ‘under representative weather conditions’. Clearly, this differs from the strict criteria definitions, in that the period of time over which exceedance can be accrued is just 10 days compared with 153. Further, ‘representative’ is open to a huge variety of interpretations and occupied or not occupied period is left moot.

Very different perceptions of the incidence of overheating are gained depending on the criterion, or criteria chosen and the ways that they are applied. This is not surprising when one considers Figure 1, noting the approximate range of the maximum running mean temperature between June and August in typical and extreme years (see Lomas & Giridharan, 2012). McGill et al. studied an eclectic mix of well-insulated dwelling types in a variety of locations. They showed that whereas 58% of monitored living rooms had more than 10% of annual hours over 25° C (Passivhaus), fewer than half of these (25%) had more than 1% of assumed occupied hours over 28°C (CIBSE) and 33% breached two of the three CIBSE adaptive criteria (Category II based). Conversely, in their study of care settings for the elderly, Gupta et al. found that 30% of flats and communal areas breached two or more of the CIBSE adaptive criteria (Category I based) whilst 70% had more that 1% of occupied hours over 28°C.

The time frame over which the hours exceeding a threshold are accumulated can also alter one’s perspective on overheating risk. Lee et al. illustrate this admirably. Using the predicted temperatures in the bedroom of a typical London terraced house, they examine the intensity and duration of exposure

[9] These actions are analogous to the decisions made about the clothes to wear for the working day ahead. Such decisions are integral to the adaptive thermal comfort concept.

to heat. Crucially, they note that overheating tends to occur in strings of successive days and that these successive days of high temperature, which will have an impact on health, can become ‘buried’ when ‘standard’ CIBSE TM52 overheating criteria are used. This may be especially so in the UK which is, compared with other more land-locked countries, prone to rapidly changing weather, with particularly warm spells, generated by stable anticyclones lasting a few days, interjected into the more normal, temperate conditions. Whether the new metric proposed by Lee et al., continuously overheated intervals (COI), which describes the intensity and duration of hot spells, gains traction with the community remains to be seen.

The paper also shows just how much the predicted intensity and duration of elevated internal temperatures depends on the future weather file chosen. There remains work to be done on the selection of current and future weather files for use in overheating assessment, in particular selection that is based on the incidence of heatwaves rather than longer-term average conditions.

Stimulated by the published papers, this section has questioned the suitability of contemporary overheating criteria and highlighted the practical difficulty of applying them for the assessment of real occupied buildings. Indeed, the plethora of health, comfort, internal temperature-based and external temperature-based criteria is something of a minefield. This is a matter that needs resolving if the research and practitioner communities are to produce a coherent, practical, reliable and reproducible post-occupancy overheating assessment methodology.

Our understanding would also be improved if the in-use assessment methodology enabled weather normalization, such that the performance of one dwelling (or group of dwellings) could be compared with the performance of others that have been monitored at a different time and/or in a different place. This is rather like the use of an agreed weather file for modelling overheating risk, but applied instead to empirical data. Such an approach would also make it possible to project forward in time and so understand the potential performance of dwellings under future (warmer) weather conditions (assuming similar occupant behaviour).

Long-term thinking also requires a decision about who the home is being designed for. Over the life of a house, its occupancy may change many times, especially if the accommodation is rented out[10]. Assessments of long-term as-built performance, and the criteria that determine this, should consider different potential occupants’ sensitivity to overheating. There is much valuable research work still to be done.

How do people respond to heat?

The previous section discussed the criteria for defining, at least for now, whether or not a building is overheated. The criteria also provide a comparative framework for comparing one building with another through modelling and monitoring. However, buildings are occupied by people and ultimately it is whether they are too hot and likely to suffer adverse effects as a result that matter, and not what the measured temperature is and for how long it lasts. It is also people who will act, or not, to ameliorate uncomfortable conditions.

It has long been accepted that, at least where comfort is concerned, people will act to try to restore thermal comfort. What constitutes comfort differs from one person to the next. What people will do when feeling uncomfortable also differs and depends on the adaptive opportunities available and their understanding of the likely impact of taking action. By way of example, the questionnaire and telephone surveys of Vellei et al. reinforced the general understanding that elderly and infirmed adults tend to feel cooler than non-vulnerable people when exposed to the same temperature. This might

[10] Reliable statistics could not be found, but in owner- occupied homes ownership is likely to vary from a few years in starter homes to a few decades for larger homes occupied by fully evolved families and those in later middle age.

explain the tendency for their heating systems to stay on in summer and their windows to be closed, thereby elevating the risk of overheating.

This also raises questions about the physiology of heat stress. What is the period (length) of time needed for acclimatization and adaptation? Is it more difficult/ more stressful to adapt to a sudden heatwave than a gradual progression to a long, hot summer? Rather than thinking in terms of a whole population, is it possible to identify those most vulnerable and unable to adapt? Should these groups have a different set of criteria which define overheating (hours of exposure/°C)?

Zhang et al. and Meinke et al. explore these issues in more detail. Zhang et al. conducted a classic, rigorous, thermal comfort study in a climate chamber but, uniquely it is claimed, focused on the thermal comfort perception of 30 healthy young (17–22 years old) rural Chinese participants, born and raised in farming villages in the hot and humid Guangdong area of southern China. In the climate chamber studies their thermal sensation, comfort and temperature acceptance was recorded when they were exposed to temperatures from 20 to 32°C and relative humidity of 50% or 70%, which yielded standard effective temperatures (SETs)[11] between 19.7 and 34.6°C. The results were compared with those previously obtained from a matched sample of urban Chinese ($n = 60$) living in naturally ventilated buildings in the same climate (Zhang, Chen, Wang, & Meng 2015).

Interestingly, there was no significant difference in the thermal sensation of the two groups and the neutral SETs were similar 26.8 ± 1.32°C (rural) and 27.1 ± 2.45°C (urban). These averages are very close to the acceptable operative temperature indicated by the BSEN15251adaptive standard for a running mean ambient temperature of about 28–29°C, which is the mean monthly temperature in Guangdong in summer (July) (Figure 1). But the inter-subject range in the neutral temperature, up to ± 2.45°C, is important to note. Such differences will mean individuals may strive for quite different 'ideal' temperatures, whilst some might be uncomfortable above 24.6°C, others could be content up to 29.5°C. These observations begin to illustrate why some households feel comfortable at temperatures that others find unacceptable (for example, see Morgan et al. below).

The thermal acceptability and thermal comfort of the two groups was, though, significantly different. The rural subjects were much more accepting of all temperatures, and were more comfortable than the urban subjects at all non-neutral temperatures. The differences between the comfort rating of the two groups was most significant ($p < 0.0001$) at the higher temperatures (SET = 32.3 and 34.6°C). The experimenters attributed this to the different expectations of the subjects, although acclimatization may also be involved.

Perhaps the transition from an active rural life, for which people have been evolutionally shaped, to a sedentary urban existence blunts our psychological capability to tolerate more extreme temperatures. Perhaps temperature sensitivity is, like obesity and allergies, yet another unwelcomed side effect of our urban lifestyle?

Meinke et al. present an ingenious experiment that explores the idea of providing advice about the effects of different adaptive options that people can take when faced with elevated temperatures. The beauty of the approach was not to tell people what to do, merely to offer some adaptive opportunities, to advise on the likely consequences of different actions and, importantly, to offer the advice at the moment it was useful, i.e., when people are getting too warm. In the experiments, the adaptive options,

[11] The Standard Effective temperature (SET) is defined (ANSI/ASHRAE, 2013) as 'the temperature of an imaginary environment at 50% relative humidity, <0.1 m/s average air speed, and mean radiant temperature equal to average air temperature, in which total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment, with actual clothing and activity level'. In the experiments, the air speed was less than 0.1 m/s, the mean radiant and air temperature were equal and the all subjects were sedentary 1.0 Met and wearing the same ensemble of 0.57 clo. Thus, it is changes in humidity and temperature alone that is responsible for the different thermal strains on each subject.

the advice offered and the way it was offered was the same for all people, but differences occurred both for the choices people made and the temperature at which adaptive action was deemed necessary.

In the experiments, young, healthy people wearing an ensemble with the same insulating properties, 0.8 clo, were asked to undertake desk-based work in an experimental office space. Each person was: (1) required to complete an initial questionnaire; (2) exposed to a gradually increasing temperature[12], (3) when indicating they were too warm (maximum time allowed two hours five minutes from the start of the temperature ramp), asked which of four corrective actions they propose to undertake; (4) provided with advice on the speed with which temperatures would change and the energy demands of the action; (5) asked to choose which actual action to undertake and take it; and finally, (6) asked to remain in the space for one hour before completing a final questionnaire. The internal space conditions were continuously monitored and comfort votes taken at intervals. Seventy-six individuals provided useful data.

The results were interesting. Firstly, despite all the participants wearing clothing of the same clo-value, the SET temperature at which people 'started to feel too warm and intended to change the conditions' varied from 25.9 to 32.8°C with a mean of 29.3°C. The figures are interesting both for their range, people 'feel too warm' at very different temperatures (see the comments above about criteria), and the mean, which is not too different from the one commonly used for the static comfort criteria 28°C (see above). Secondly, there was a clear tendency for people to propose (n = 65) and adopt (n = 61) fast-acting measures, removing items of clothing or opening the window (and the questionnaires confirmed this preference). Thirdly, there was a tendency for the actual action (after the advice) to be the same as the proposed action (humans are not wont to admit they were wrong), although more of those that proposed turning on the air-conditioning (n = 9) actually did something different (n = 5) when advised that it was slow acting and energy intensive. Finally, very few (n = 2) proposed using the ceiling fan, although more (n = 9) actually did when advised of the fast acting, low-energy characteristics. Perhaps there is a greater role for ceiling fans in mitigating overheating discomfort.

When windows were used, there was a greater overall improvement in thermal sensation and comfort than expected purely from the change in SET temperature. Perhaps a small sensation of air movement, the exposure to fresh air or even simply the connection with the outside world (e.g., bird song), or some other factor, confers greater benefits from windows than one would expect. In this regard Meinke et al. note the work on thermal alliesthesia of Parkinson, de Dear and others (e.g., Parkinson & de Dear, 2015).

The controlled experiments clearly support the general level at which current overheating thresholds are set. Although they cannot pass judgement on the veracity of the adaptive thresholds for use in homes, they do clearly show the very wide range of conditions over which different people will or will not feel comfortable. One might readily imagine therefore that identical houses, exposed to the same weather conditions, can have quite different internal temperatures, and whilst one may be deemed to overheat the other may not. The difference lies in the actions of the occupants, not because one household is unable to regulate the indoor temperature properly but because they are actively seeking a warmer interior (see the commentary below on the work of Morgan et al.). Given this, is it possible to decide, on the basis of in-situ measurements, whether the basic house design is or is not resilient to overheating?

How widespread is overheating?

Whether or not a building overheats in practice depends on the interplay of the local climate, the

[12] Air speeds were under 0.1 m/s, relative humidity was 35%, and the surface and air temperatures were the same.

building's construction and, as noted above, occupant behaviour. This interplay means that the observed pattern of overheating, as measured by any chosen criterion or criteria, can be complicated and sometimes counter intuitive.

In this issue, summertime temperatures recorded in homes from the south of England to the north of Scotland are reported. They cover a range of build types and occupant characteristics and so enable some of the overriding factors that influence indoor temperatures to be uncovered. In many of the studies other environmental physical and human factors are recorded which enables insight into the possible causes of any overheating that was observed.

Beginning in the south-west of England, Vellei et al. report temperatures recorded in two successive summers in 55 newly retrofitted low-rise social dwellings; 17 flats in blocks under four stories and the rest one or two storey homes. Data were collected during the summer (1 May–30 September) of 2014 and 2015, neither of which was particularly warm or experienced heatwaves. Questionnaires were delivered at the end of summer 2014 and during the summer of 2015, and telephone surveys were also conducted. The researchers were especially interested in determining if overheating was more prevalent in overcrowded homes, i.e., those with more than five occupants, or the homes of vulnerable households, i.e., those with occupants over 65 years, those with disabilities or with long-term illness.

As both summers were cool, the incidence of overheating was low. In the study, only five living rooms and kitchens, for which acceptable data were retrieved, overheated in 2015. Kitchens were significantly warmer than other rooms, perhaps due to the higher internal gains. Rooms below roofs were found to be significantly warmer than other rooms, thus 15 of 18 bedrooms that yielded usable data overheated (CIBSE 1%/26°C criterion[13]) in 2014.

In 2014, though not in 2015, the mean temperature in vulnerable households was significantly higher (0.6K on average) than in non-vulnerable households. A contributory factor was that 10 of the 13 vulnerable households kept their heating system on all summer, whereas just one-third of the non-vulnerable households did. Vulnerable households also used their windows less, and so the internal CO_2 levels were higher. This limited use of windows also contributes to enhanced overheating risk.

Gupta et al. focus very specifically on overheating and the elderly and vulnerable. Monitoring, interviews, questionnaire surveys and ethnographic studies took place in four buildings in England, two in the south-east, one in the north-east and one in the south-west. They obtained useful temperature data from 11 bedrooms, six living rooms (extra-care) and eight communal areas (care homes). All were monitored in the summer of 2015, which was a relatively cool summer, but with one hot spell of two days where the peak ambient temperatures reached 34°C. They recorded overheating using the CIBSE 1%/28°C and 1%/26°C criteria (bedrooms) in 16 of the 17 bedrooms and flats and in five of the eight communal areas. In the context of healthcare and the elderly it is also pertinent to note that the mean temperature was over 24.5°C in all bedrooms; Public Health England note that 'heat related deaths are expected to increase above 24.5°C' (PHE, 2015). The authors note that 'there is a lack of evidence on appropriate temperature thresholds (for health and thermal comfort) within the care sector, and specifically for older people'. In fact, the papers in this issue suggest that this is true for many types of spaces and occupants.

The authors observed notable temperature differences in similar rooms, leading them to conclude that 'overheating is as much to do with heat management within individual rooms and is as important as overall building design'. Getting to the bottom of this is difficult, especially because those in care are physically and cognitively frail and so surveys of thermal comfort, however delivered, can be unreliable. Surveys of the buildings and informal discussions with the occupants and carers did, however, shed some light on the matter. These showed that ventilation opportunities were restricted: windows were hard to use, especially for the elderly, because of the design of the opening handles; trickle vents were awkwardly located and too fiddly; restrictors on the degree of window opening limited ventilation even

[13] In this section a short-hand reference to the substantive criteria(on) being used is given; for details, see Table 2.

when they were open; and some trickle vents were painted over. Internal heat gains were high because centralized heating and hot water systems remained on, continuously circulating hot water around the building, even in summer. Many of these problems could be managed, but there is a lack of agency amongst the staff and residents[14]. This ‘tragedy of the commons’ can result in no one taking the initiative to fix chronic, or even acute, problems that lead to high internal temperatures. Thus, buildings that, by virtue of design and location, may not be predicted to overheat can do so in practice. Mavrogianni et al. take the reader on a tour of a substantial body of work that encompasses monitoring and two forms of modelling: dynamic thermal modelling with EnergyPlus, and the development and use of a regression-based meta-model. The aim of the whole is to develop a way of predicting the overheating risk in the large stock of homes in Greater London; an area of circa 8.5 million people and with an intense urban heat island. Here we focus on the monitoring work.

Temperatures were gathered from a convenience sample of 101 homes, of which data collected during August 2009 are presented in the paper. A home energy performance certificate survey was also undertaken to capture the dwelling’s characteristics and a questionnaire was delivered to understand occupant behaviour, especially with regard to window opening. However, this was delivered after the summer was over and so may suffer from recall bias.

Around 19 living rooms had maximum temperatures over the CIBSE threshold of 28°C (between 08:00 and 20:00 hours)[15] and around 46 bedrooms had maxima over 26°C (between 20:00 and 08:00 hours). Whilst the authors call this a ‘significant number’, it is difficult with such analysis to make any firm conclusion about overheating risk.

More valuable perhaps are the findings of the occupant survey. This showed that 75% of occupants use curtains or blinds on hot days. However, window-opening behaviour was very mixed. On a very hot day, 38% of respondents would open most windows during the day, and 53% would keep only one window open at night. However, window opening was curtailed in many homes due to security or noise concerns: ‘More than half of respondents … were unable to open windows when needed for security reasons’ and ‘even on a very hot day more than one in five respondents … . would not tend to open any windows at night’ and ‘one-third… would not open windows due to high external noise levels’. This survey therefore begins to shed a light on the magnitude of the barriers to ventilation cooling in a city environment. As expected the results illustrate the constraints to overheating control imposed by urban security and noise concerns.

Baborska-Narożny et al. present the results of an overheating investigation of a block of flats in the city of Leeds. Flats have frequently been identified as particularly at risk of overheating. The paper presents a short, spatially and numerically constrained but deep study, which included an excellent ethnographic investigation. The 10-storey block of flats, built in the 1950s, had been refurbished in 2012 to produce one and two-bedroom flats with a single aspect. Thus, whereas previously cross ventilation had been possible, the refurbishment enabled only single-sided ventilation. The refurbishment produced thermally lightweight flats with low ceilings. Windows varied significantly in size, the ground floor ones had trickle vents, the upper floors did not[16], and all had restrictors to prevent opening beyond 100 mm. This is common practice in the UK on safety grounds. All flats had mechanical extract vents in the kitchens and bathrooms.

Temperatures were measured in 18 bedrooms and living rooms between 24 June and 31 August 2013, which was a warm period and included a hot period (peak ambient temperature of 29°C) which triggered a heatwave alert. The researchers undertook a questionnaire survey of the residents in all 200 flats (n = 95). More interestingly, they conducted ethnographic surveys of temperature control practices. This focused on six flats on the ninth and tenth floors, which had different overheating occurrences. They visited homes every seven weeks to make walk-round observations, take

[14] The authors note the lack of staff training and a rapid staff turnover as contributory factors.
[15] August data only, CIBSE criteria are not strictly applied.
[16] The authors site supply-chain problems as the reason for no trickle vents on the upper-floor windows.

photographs and have conversations with the occupants.

Overheating was widespread, with 44% of bedrooms and 28% of living rooms exceeding the CIBSE 1%/26°C and 1%/28°C thresholds during occupied hours[17]. Some 43% of respondents to the survey complained that their flat was too hot: 'Like an oven in summer'; 'The heat is unbearable.' The investigators attribute this in part to the fact that many occupants did not keep their extract ventilation systems running in the kitchens and bathrooms to draw (cooling) external air through the flat. However, the noise made by the extract fans was a barrier, which was a stated problem in 23% of flats. A variety of trial-and-error procedures were used by occupants in their attempt to combat the stifling temperatures, such as: wedging open the door to the flat to enable cross-venting and ignoring the manufacturer's stickers prohibiting the opening of windows beyond the range of the restrictors. In later phases of the study, after the temperatures reported above had been measured, the occupants sought the researcher's advice on combating the high temperatures. Advice was implemented by some occupants; an example of action-research having direct and immediate impact.

The barriers to overheating control noted in this study are not uncommon. In the UK extract fans are cheap, flimsy and often noisy, and it is the noise that frequently curbs their use. Requirements on the noise levels of extract ventilators, especially in new-build premises which fall under the scope of the building regulations, would be a good thing.

Modern, well-insulated homes are perhaps more at risk of overheating and McGill et al. and Morgan et al. specifically probe this question. Both report temperatures measured in new homes studied as part of the Innovate UK Building Performance Evaluation programme[18]. Whilst McGill et al. present a meta-analysis of data from 60 dwellings, Morgan et al. focus specifically on houses in Scotland.

In McGill et al. indoor temperatures are reported from 53 homes spread across the country. They covered a range of house types and construction modes, though timber-frame construction constituted 63% of the sample. The data collected were patchy, but the overheating assessment of bedrooms and living rooms using static criteria was conducted for 77 bedrooms and 53 living rooms. The CIBSE adaptive criteria (TM52) were used to analyse the summer temperatures in the living rooms of 46 dwellings.

The Passivhaus 5%/25°C criterion was exceeded in 38% of bedrooms and 58% of living rooms, whilst the CIBSE criteria were exceeded in 25% of living rooms (5%/28°C) and 62% of bedrooms (1%/28°C). The CIBSE adaptive criteria (Category II based) were exceeded by 33% of the living rooms. The authors note the similarity in the temperatures measured in bedrooms and living rooms. Although the incidence of overheating was greater in the thermally lightweight homes and homes with mechanical ventilation with heat recovery, care must be exercised when interpreting this. As the dwellings are geographically distributed, they are exposed to different weather conditions and there is no easy mechanism for normalizing to a common weather condition.

Overheating in the UK is generally considered to be a phenomenon found in the milder, southerly parts of England. However, Morgan et al. demonstrate that when insulation levels are particularly high, as in Passivhaus dwellings, overheating may even occur as far north as Inverness in Scotland. They report temperatures measured in the living room and main bedroom of 26 low-energy and Passivhaus dwellings across Scotland, of which 21 were thermally lightweight.

Static criteria (Passivhaus) were used to assess overheating using all the hours in 2013. Fifteen of the bedrooms and 18 living rooms had more than 10% of annual hours over 25°C, and 20 bedrooms and 18 living rooms more than 5% of hours over 25°C. The authors also examined the frequency of occurrence of average (of the two rooms) temperature over 25°C in each month; all the houses had more than 11% of July hours over 25°C. A matrix of 32 features that might tend to increase overheating risk was developed: features such as top floor or not, high window-to-floor area ratio,

[17] The researchers took trouble to record when the flats were and were not occupied
[18] The Innovate UK, Building Performance Evaluation programme funded 53 projects, which included 250 energy-efficient dwellings

south-facing glazing. However, there was ‘no discernible relationship between the incidence [of overheating] and the potential factors causing overheating’. This suggests that a simple ‘tick box’ approach to identifying whether or not a dwelling might overheat may not be successful.

The effect of occupant behaviour perhaps dominates in these highly insulated dwellings and leads to some overheating whilst others of very similar design and thermal efficiency do not. For example, in identical adjacent homes the annual average temperature exceeded 25° C for 46% of hours, whilst next door 25°C was exceeded just 13% of the time. Interestingly, in the first of these houses the occupants reported no overheating, whilst next door the occupants were concerned.

The authors speculate that ‘in certain households, what is being defined … as overheating is simply the desired comfort range of some occupants’. This may well explain why, overall, there was no relationship between the reporting of overheating by occupants and the occurrence of more than 10% of annual hours over 25°C. Only in about 50% of cases did this criterion’s assessment match occupant reporting (Table 3), in the other 50% either the criterion reported overheating and the occupants did not or vice versa. The observed diversity of occupants’ response to elevated temperatures might therefore be demonstrating in real homes the diversity of response observed in the experiments of Meinke et al. and Zhang et al. (see above).

Table 3. Comparison of the number of living rooms and bedrooms reported to overheat, and the number deemed to be overheated by the Passivhaus criterion.

At the design stage, just four homes reported by Morgan et al. were deemed likely to overheat when assessed using the UK Standard Assessment Procedure (SAP), Appendix P. Likewise, all the Lockerbie projects had more than 10% of annual hours over 25°C, whereas the PHPP predicted incidence was just 0.2%. Clearly, there is a massive gap between predicted and as-built performance. This observation confirms the view of others. For example, the UK Zero Carbon Hub has observed that the SAP model ‘is not separating out properties which are genuinely at risk of overheating’ and so when applied in design practice the effect is that ‘no one fails Appendix P’ (ZCH, 2015).

One route to understanding the inherent overheating risk posed by different construction types is to directly compare the alternatives. Birchmore et al. compares the measured temperatures in a typical New Zealand home with those in a similar modified home. Temperatures were recorded in the open-plan living area and bedroom at hourly intervals over the summer of 2011 (1 December–28 February) and compared for periods ranging from a month to a single day[19]. The percentage of hours over 28°C (living) and 26°C (bedroom) and above the TM52 adaptive threshold (Category II) was used as an indicator of overheating. Not surprisingly, since there were no occupants to effect ventilation cooling, the homes overheated significantly (in the bedroom of the control house temperatures reached 42.5°C).

The principal interest here is the idea of matched-pair testing as an avenue to direct assessment of overheating reduction methods. The resolution is much better than have to be accounted for, which requires some sort of model. The weakness of the Auckland study is the lack of occupant actions that could ameliorate the extreme internal temperatures, but it is possible to introduce simulated occupants to effect such adaptations. This was first done at least 30 years ago (Rayment, Cunliffe, & Morgan, 1983). One could imagine today that rather sophisticated, computer-controlled ventilation, shading and internal gain schedules could be programmed, which would enable the performance of alternative overheating reduction methods to be measured in a controlled, repeatable and systematic way.

Thomas describes a post-occupancy survey of seven office buildings, three in Australia and four in India, all adopting different passive and hybrid forms of ventilation and mechanical cooling. The paper considers the challenge for designers and building managers with energy-efficiency concerns to ensure that the air-conditioning is used only when and where it is needed. The need to avoid unmanageable complexity is also paramount (e.g., Bordass & Leaman, 1997).

[19] In a subsequent year the control house was modified to improve roof ventilation.

This study also highlights the way that noise can interfere with ventilation aspirations. In a domestic setting it is often street noise that curtails ventilation by opening windows, in this case it was internally generated noise in the open-plan offices designed to ensure unimpeded air flow. The paper also draws to readers' attention the extent to which ceiling fans are used to provide cooling in office buildings in India, even being operated concurrently with the air-conditioning system. Whilst this approach is extremely common in India, it is seldom used in buildings in more developed countries, except as a semi-decorative feature, e.g., in restaurants and conservatories, or as an emergency measure when temperatures are uncommonly high, in which case desk or floor-standing fans tend to be used. It is worth dwelling on the potential of ceiling fans to combat heat, especially in care settings, of the type discussed by Gupta et al.

All three of the key design guides explain the helpful role that fans my play in reducing thermal discomfort in hot conditions. The CIBSE guide indicates that a ceiling fan generating a 0.5 m/s air speed over a person could be used when temperatures exceed 25°C to give an improvement in thermal comfort equivalent to reducing the space temperature by about 2 K (CIBSE, 2015, pp. 1– 4). Likewise, the ANSI/ASHRAE Standard 55 permits the use of occupant-controlled ceiling fans above an operative temperature of 25.5°C, and also notes the effect as equivalent to reducing the SET temperature by 2K at 0.5 m/s (ANSI/ASHRAE, 2013). Finally, and importantly, BS EN15251, which underpins the CIBSE TM52 adaptive comfort approach, allows the upper bounds of the thermal comfort envelope to increase when the internal operative temperature is above 25°C (which covers the whole range of ambient temperatures to which the adaptive comfort thresholds apply; Figure 1). At an air speed of 0.6 m/s the upper threshold of the comfort envelope is raised by 2K, the maximum allowable air speed is 0.8 m/s[20]. Modelling has shown that fans can significantly improve the resilience of healthcare buildings to climatic warming (Lomas & Giridharan, 2012) and they could do likewise in dwellings.

Can we predict overheating?

Symonds et al. provoke the question of whether researchers and practitioners need to think carefully about the role of modelling to designing buildings that will not overheat. Their paper explores the use of the well-known dynamic thermal model EnergyPlus to understand overheating in the existing UK housing stock. More conventionally, though, models are used to predict overheating risk at the design stage. Before reflecting on Symonds et al. it is worth thinking about this application first.

It was noted above, following the examination of the work of Morgan et al., that there was a massive gap between the predicted incidence of overheating by the SAP programme and PHPP and the actual incidence of overheating as measured by hours over 25°C. This is not so surprising because the PHPP and the SAP are steady-state models which are being applied to an inherently dynamic problem and so they cannot possibly capture the full complexity of the thermodynamic processes at play. Even dynamic thermal models can struggle to predict accurately internal summertime temperatures in buildings. First, because predictions are very sensitive to quite small changes in model input parameters and yet many inputs are highly uncertain: 'At the stock level there is much uncertainty associated with inputs [especially] with regard to occupant behaviour' (DECC, 2015). Second, because predictions can be very sensitive to the way that the equations within the model strive to represent the thermal physics of the problem. Thus, even if the input data is precise, the dynamic model used, and the way it is configured, can have a huge impact on the predictions.

To illustrate the point, in the early 1990s the current lead author reported a study in which three reputable energy models were fed with identical and/or compatible[21] input data about a well-insulated, multi-zone house (Lomas, 1996). Simulations using both Scottish and London weather were undertaken for different construction types, south-facing window-to-wall ratios and window types. The good news was that the three models produced compatible information about whether each design

[20] Above this speed, lightweight objects, notably paper, may move around.

[21] Models use different ways to represent the same physical feature. Great effort was directed to ensuring the inputs chosen were compatible.

variation would lead to higher or lower internal temperatures and they predict reasonably well by how much the temperature might change. This gives confidence that the models would drive a designer towards making the correct design choices in order to reduce overheating risk.

Unfortunately, the absolute predicted temperatures varied from one model to the next, for example the predicted annual maximum and minimum air and operative temperatures varied by about 2 K; which might not sound too bad. Crucially, however, these temperature differences translated into huge differences in the predicted annual hours over a chosen threshold (in this case 27°C). For air temperature one model predicted 67% more hours over 27°C than another and for operative temperature up to 250% more. Clearly, as currently framed, overheating criteria make it inherently difficult to predict the absolute magnitude of overheating that a building will experience.

It is against this background that one should reflect on the work of Symonds et al. Their paper reports a substantial investigation into the use of dynamic thermal modelling, not for building design purposes but to understand how changes to the weather, through climatic warming, might affect the exposure of a population to elevated indoor temperatures. They were concerned with the English housing stock, as represented by the 823 English homes monitored as part of the Energy Follow-up Survey (DECC, 2013) to the English Housing Survey (EHS) (DCLG, 2011). The dwellings covered the full range of types, constructions, ages and locations and so are thought to represent the full diversity of the English stock.

A home energy survey, of the type undertaken for energy performance certification, was also undertaken. With such a survey it is highly unlikely that the precise geometry, thermo-physical parameters of materials, background infiltration rate, and site shading etc. will be known. The modellers therefore had to make random assumptions, for example, about house orientation, and they modelled each dwelling up to five times to account for different potential occupant behaviours (internal gains and window opening, for example). The weather data were taken from the nearest meteorological station. These difficulties are a practical inevitability when trying to model large stocks of buildings.

The predictions of EnergyPlus were compared with the monitored summertime (May–September) daily maximum temperatures recorded in living rooms (n = 768) and the mean summer maximum temperature (i.e., the average of the 153 daily maxima) recorded in the living rooms and bedrooms (n = 772). The results were poor; as the authors note ‘the model struggles to predict the maximum temperature in individual dwellings and performance was worst when outdoor temperatures were high’, and ‘the model tended to perform worse when predicting bedroom temperatures … ’. The root mean square error (RMSE) of the predicted daily maximum living room temperatures over the whole summer was 2.66°C. It increased as the ambient temperature increased, up to 4°C or more for some groups of dwelling type. The results suggest that differences between the measured and predicted frequency of overheating, as defined by any chosen criterion, would be huge (see above); but the paper does not present such an evaluation.

Considering the study of Symonds et al. together with the findings of previous work, it is evident that the prediction of reliable absolute values of internal temperature by dynamic thermal models is very difficult, at least for rooms in UK dwellings. And when key input parameters are unknown, useful predictions may be impossible to obtain. If one thinks about the thermodynamics of the situation, perhaps this is not so surprising. Thermal models have been developed from a building physics perspective, and sophisticated, first principles, dynamic thermal models are based around modelling the fundamental thermo-physical processes of conduction, convection and radiation with particular emphasis on predicting heat fluxes through the thermal envelope in response to changing ambient conditions. Fabric heat exchange is very important when wintertime heating energy demands in cool and cold climates is being predicted or cooling demand in hot and sunny climates. However, in summertime, in cooler climates, the ambient temperature may be very similar to the indoor temperature, so heat fluxes through the opaque elements are small.

To a first approximation the indoor temperature might be set as similar to the ambient temperature, perhaps with some time delay and thus contribution from previous days' temperatures. Beyond this, what matters for accurate overheating prediction is the modelling of ventilation, instantaneous radiant fluxes through glazing, internal heat gains and the absorption, or not, of heat by internal thermal mass. But accurate first-principles modelling of these is very difficult, if not impossible, for existing dwellings and certainly for large stocks of dwelling; the data needed by the model are simply not available, are very uncertain, or impractically difficult and expensive to obtain. For example, accurate ventilation modelling may require the creation of an inter-zonal air flow network and so knowledge of the sizes and locations of envelope and inter-zonal air-flow openings, and an understanding of how the openings change with time, for example, as occupants open and close vents and windows. Solar gain is in principle easier but, as with ventilation modelling, needs data on the area of glass and its orientation, external shading and the position of curtains, blinds or other shading features. Internal heat gains are simply values supplied to the model by the user and, odd as it may seem, the thermal mass available for thermal exchange depends on the building and its construction, especially that of internal walls and floors, the furnishings and the fittings.

It is the current authors' contention that sophisticated dynamic thermal models[22] are not the most effective way to reliably predict the current and future overheating risk in existing stocks of dwellings. Instead, given the ease and low cost of temperature monitoring and the imminent availability of smart meters, home-access devices and ubiquitous internet connectivity, data-driven models, either grey or black box, may be the way to go.

What next?

A 'perfect storm' of interacting factors was described above that can cause summertime overheating: the drive for energy efficiency and decarbonization, the changing climate with increasingly hot summers and heatwaves, urbanization and urban heat islands, the incessant drive to reduce construction costs, increasing land and property prices, an ageing population, the technical ability to identify and quantify the problem, and the profound social and cultural lack of knowledge about what to do when confronted with heat. But these are not so much factors as political, demographic, sociological, economic, technological and climatic trends, and all are trends that will lead to more serious overheating in future unless active intervention occurs. The papers in this issue have begun to identify what those interventions should be, when they should be undertaken and by whom.

Before progress can be made, however, it is clear that there needs to be a robust definition of overheating and one that can be used to assess actual occupied buildings, rather than abstract theoretical models of buildings. There is a lack of consensus surrounding the definition, measurement and reporting of overheating in buildings.

The latest adaptive comfort assessment methods presented by CIBSE and ASHRAE go some way to addressing this, but there are still many issues to confront. The results of modelling studies are influenced by the choice of occupancy profile, internal gains and the weather file chosen, whilst overheating assessments in existing buildings can be affected by the choice of monitoring period as well as the assumed occupancy. It has been suggested that some way of normalizing monitored temperatures would be invaluable in enabling comparisons across different homes, occupied by different people, monitored at different times. Further research is also required to translate monitored data into a credible overheating risk assessment. Adaptive methods, derived from surveys in offices, have been assumed for the home environment. Their application in bedrooms, where the adaptive opportunity may be more limited at night, is particularly contentious, not least because there is very little published work about the impact of temperature on sleep quality.

It is also important to disaggregate the key factors that contribute to overheating risk, although simple checklists are unlikely to work well. Whilst the design of a building will play a major role, correct

[22] And steady-state models, like SAP and PHPP, cannot possibly produce credible overheating predictions.

operation, such as use of windows or shading devices, can be equally important. This was clearly demonstrated by Morgan et al., where overheating varied considerably between two neighbouring ‘identical’ Passivhaus dwellings, leading the researchers to conclude that ‘occupancy overrides design’. Communicating the ‘correct’ way to operate a building during hot weather will be one of the key challenges, particularly for countries such as the UK, where there is little historical experience of overheating. The challenge is exacerbated in dwellings occupied by the elderly. Perhaps occupant warning systems should be developed, taking advantage of low-cost sensors and the rapidly developing technologies associated with the ‘connected home’?

Targeting resources, both for adaptation measures and advice, will require further evidence to identify the types of both dwellings and occupants most at risk from overheating. Large-scale field studies are difficult, costly and time-consuming, but are vital to strengthen the evidence base which, to date, has been provided mostly by modelling studies. A mechanism for ‘normalizing’ the data from field studies, so one can be reliably compared with another, could bring much greater insight.

The papers and arguments presented here suggest that first-principle building physics models are unlikely to make reliable predictions of the incidence of overheating in occupied dwellings, and simpler predictive models are likely to be even worse. Perhaps empirically derived models have a valuable role to play?

The current body of knowledge can be confusing for professionals working in the housing sector and building regulations, particularly in the UK, do not sufficiently address the issue of overheating as they currently stand. Clarity on regulatory guidance and enforcement will provide a steer to developers and help to ensure that new buildings will perform correctly, both now and under future (warmer) climates. Regulatory requirements to minimize overheating might usefully cover: the position and orientation of buildings; a consideration of pollution and noise issues; the provision of adequate adaptive opportunity through ventilation and shading; and suitable adaptive controls and clear instructions in the correct use of these at handover to the occupants.

Further research is also required by public health bodies and health epidemiology researchers who should be working closely with those researchers doing field monitoring in dwellings. This will lead to a better understanding of the impacts of the physiological responses following exposure to heat, particularly amongst vulnerable groups. The effects of heat exposure duration, and the acclimatization process over successive hot days, will inform the debate around adaptive thermal comfort.

Acknowledgements

As guest editors we have had the privilege of reading and digesting the work of 12 research teams. It has been a pleasure to read their work and we are grateful for their participation in this special issue and their willingness to bring their findings to the attention of the wider world. The lead author (K.J.L.) of this editorial thanks the second author for his tremendous assistance in the creation of this issue. Stephen moved on from academia after nine years, contributing in later years to our knowledge about overheating in buildings. His contributions, comments and edits to this editorial were most valuable. Any faults with this editorial are entirely those of the first author, and criticism should be directed there.

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Figure 1: Thermal comfort and overheating criteria. Adapted from Lomas & Giridharan (2012) to show static criteria and the effect of a ceiling fan.

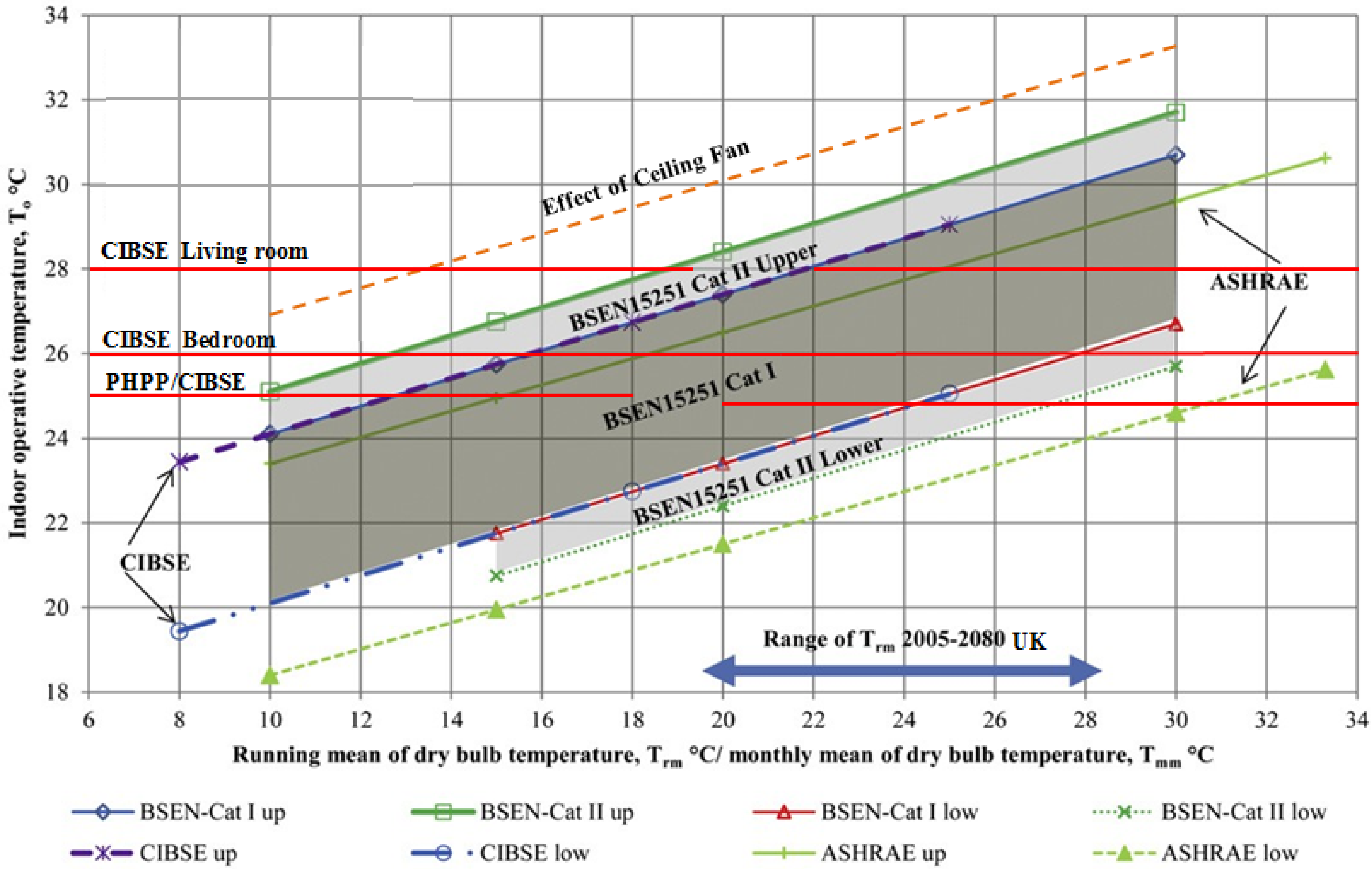

Table 1. Articles in this special issue, Overheating in Buildings: Adaptation Responses

Authors	**Title**
K. J. Lomas and S. M. Porritt	Overheating in buildings: key lessons from research
L. E. Thomas	Combating overheating: mixed-mode conditioning for workplace comfort
Z. Zhang, Y. Zhang, & L. Jin	Thermal comfort of rural residents in the hot–humid area
A. Meinke, M. Hawighorst, A. Wagner, J. Trojan, & M. Schweiker	Comfort-related feedforward information: occupants' choice of cooling strategy and perceived comfort
R. Birchmore, K. Davies, P. Etherington, R. Tait, & A. Pivac	Overheating in Auckland homes: testing and interventions in full-scale and simulated houses
M. Baborska-Narożny, F. Stevenson, & M. Grudzińska	Overheating in retrofitted flats: occupant practices, learning and interventions
C. Morgan, J. A. Foster, A. Poston, & T. R. Sharpe	Overheating in Scotland: mapping overheating factors in occupied homes
R. Gupta, L. Barnfield, & M. Gregg	Overheating in care settings: magnitude, causes, preparedness and remedies
W. V. Lee, & K. Steemers	Exposure duration in overheating assessments: a retrofit modelling study
A. Mavrogianni, A. Pathan, E. Oikonomou, P. Biddulph, P.Symonds, & M. Davies	Inhabitant actions and summer overheating risk in London dwellings
G. McGill, T. Sharpe, L. Robertson, R. Gupta, & I.	Mawditt Meta-analysis of indoor temperatures in new-build housing
P. Symonds, J. Taylor, A. Mavrogianni, M. Davies, C.Shrubsole, I. Hamilton, & Z. Chalabi	Overheating in English dwellings: comparing modelled and monitored large-scale datasets
M. Vellei, A. P. Ramallo-González, D. Coley, J. Lee, E. Gabe-Thomas, T. Lovett, & S. Natarajan	Overheating in vulnerable and non-vulnerable households

Table 2: Summary of Monitoring Studies in Domestic UK Buildings

				Weather		Monitored data			Other information			Overheating analysis		
Authors[i]	Location of dwellings[ii]	Number[ii] and sample	Description	Source of data	Prevailing conditions	Monitoring period analysed[iv]	Temperature data analysed	Sensors and recording frequency[v]	Property survey	Quest'aire survey	Other data collected	Static criteria	Adaptive criteria	Other
Mavrogianni et al.	Greater London, England[M]	101 Dwellings Convenience sample.	Wide range of types, ages and construction types.		Slightly cooler than normal. Five day hot spell 29/6 to 03/7	2009 01/8 to 31/8	Main living room. (101) Main bedroom. (101)	HoboU12 Temp. 10 min.	EPC surveys, during winter 2009.	Interviewer-assisted quest'aire.	Outdoor temperature at 8 dwelling locations.		-	Max, min and mean temperature in both rooms.
Symonds et al.	Distributed across England.	823 Dwellings From the Energy Follow up Survey (EFUS) to the Eng. Housing Surv. (EHS)	Wide range of types, ages and construction types.	Ten MIDAS[vi] weather stations.		2011 01/05 to 30/09	Living room (768) Bedroom (772) Hallway (0)	Tiny Tag Transit. Temp. 20 mins.	Yes, using EFUS protocol[vii]	Yes, using EFUS protocol.			-	Mean daily maximum temperature for each group of dwelling types.
McGill et al	Across England, N. Ireland, Scotland and S. Wales[M]	53 Dwellings From the Innovate UK BPE Prog[viii]	New, post-2008. Energy efficient dwellings. Wide range of types. Most timber framed (33)	Data from nearby airport.		Year within 2012-2014 for static criteria. 01/05 to 30/09/13 for adaptive criteria.	Living room (53) Bedroom (77)	Various sensors, differs between houses. Temps. 5 mins.	Yes	Yes		Each room - PHPP criterion10%/25^{o}C & CIBSE 5%/25^{o}C. Also, living room CIBSE 1%28^{o}C, bedroom 1%/26^{o}C. Assumed occupancy periods.	CIBSE TM52 Cat. II all three criteria. Living rooms only.	
Foster et al	Six sites in Scotland[M]	26 Dwellings From the Innovate UK BPE Prog.	21 low energy homes & 5 Passivhaus designs.	-	Overall average year but sunny and warm, with heatwave in July.	2013 Calendar year	Living room (26) and main bedroom (26)	EnOcean wireless sensors. Temp. and RH 5 mins. And window contact sensors	Yes	Yes	Semi-structured interviews	Each room - PHPP 10%/25^{o}C and 5%/25^{o}C over whole year.	-	Percentage of average (whole house) hourly temps. over 25^{o}C in each month. .
Boborska-Narovozny et al	Leeds, N. England.	18 Dwellings In a single ten storey block	1960's tower, refurbished in 2012. All flats.	MIDAS Bramham	Warm compared to long-term average. Heat wave alert	2013 24/07 to 31/08	Living room (18) and bedroom (18)	iButton Temp and RH 30 mins.	Yes	BUS[ix] questionnaire from 95 households in the tower.	Ethnographic survey and interviews, 6 flats, every 7 weeks.	CIBSE 1%26^{o}C threshold bedrooms, 1%28^{o}C threshold living rooms during occupied periods. Occupied periods	CIBSE TM52 Cat. II Criterion 1 only. Living and bed rooms.	

					01/08.							determined by survey.		
Vellei et al.	Exeter, SW England[M]	55 newly refurbished dwellings. All social housing[x]. 17 vulnerable households.10 overcrowded not vulnerable. 29 not vuln. or overcrowded.	Mix of ages from 1920 to 1990. Low-rise flats (22), detach'd (3), semi-detach'd (17), mid-terr. (9), end terrace (4).	2014 from 6 existing met. stations in Exeter. 2015 form dedicated met. station.	Neither year atypical or extreme. No heat waves. Summer 2014 warmer than 2015	2014 01/05 to 30/09. 2015 01/05 to 30/09.	Living rooms (41/31[xi]), bedrooms (18/25), kitchens (17/16).	Temp., Relative humidity, CO_2 & motion sensing. 5 mins. Radiator temps[xii]	No, but local authority records.	Yes	Telephone interviews.	CIBSE 26^{o}C threshold for bedrooms. Assumed occupancy period.	CIBSE TM52 Cat. I for vulnerable households, Cat. II others All three criteria. Living rooms and kitchens Assumed occupancy periods.	
Gupta et al	England, Four sites in N, SW, SE (2)[M]	Two Care homes (N, SE) Two extra-care homes (SW,SE)	Extra-care post 2006, Ecohome, BREEAM excellent. Care Pre-1990 and 2005.	On site	Generally cooler than average but hot on 1st July.	2015 19/06 to 30/09.	Living rooms (6), bedrooms (11), communal areas (8), offices (8).	Hobo U12 Temp. and humidity. Also iButton. 15 mins.	Yes	No	Outdoor temp. and humidity. Semi-structured interviews, designers and managers	CIBSE 1%/26^{o}C bedrooms, 1%/28^{o}C other rooms.	CIBSE TM52 All three criteria. Cat. I care spaces, Cat. II offices	

[i] Studies are ordered by date of first monitoring period.
[ii]Paper includes location map where indicated thus [M].
[iii] Number of dwellings for which some reliable <u>temperature</u> data was obtained, or reported in the paper. This is a subset of all the monitored dwellings in some case. More or less households may have supplied questionnaire or had a physical property survey.
[iv]This is the monitored temperature data period analysed in the paper, the total period of monitoring was often longer.
[v] Invariably reliable data was not obtained continuously for all rooms.
[vi] MIDAS – UK Meteorological Office Integrated Data Archive System
[vii] For EFUS protocol see DECC (2013)
[ix] BPE - The Building Performance Evaluation Programme, funded by Innovate UK, to evaluate energy and environmental performance of 250 new dwellings. See (Palmer, Godoy-Shimizu, Tillson and Manditt, 2016)
[x] BUS – Building Use Studies questionnaire, see e.g. Leaman, Stevenson and Bordass (2010)
[xi] Housing provided by Local Authority for rent. Vulnerable households have an over 65, disabled or long-term ill person. Overcrowded homes have five or more occupants.
[xii] First figure is number for summer of 2014, second for 2015.

Table 3. Comparison of number of living rooms and bedrooms reported to overheat, and the number deemed to be overheated by the Passivhaus criterion. Derived from Morgan et al. 2017.

		Overheating identified by occupants?		
		Yes	No	Total
More than 10% of annual hours over 25^{o}C	Yes	19	15	34
	No	12	6	18
	Total	31	21	52