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Temperature, Thermal Comfort and Health in Homes of Older People

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Summary

Globally, populations are ageing and the UK is no exception. By 2050 it is anticipated that almost a quarter of the population will be aged 65 and over, compared to 18% currently. Evidence suggests that many older people wish to remain in their home as they age, but in doing so may compromise their health and longevity. Older people are known to spend over 90% of their time indoors, often in poor quality housing. As the demographic with the highest prevalence of chronic health conditions, housing that exacerbates this is concerning. Despite a relatively mild climate the UK excess winter death (EWD) rate is the highest in Europe, and with 92% of the 28,870 yearly deaths occurring in the 65+ demographic, older people are most vulnerable. By contrast, less extreme summers lead to lower instances of summertime mortality, however, climate change is likely to alter this. Extreme temperatures found in homes of older people seem to increase their susceptibility to morbidity and mortality, but despite this very little is known about older people's thermal comfort and indoor environment. This thesis presents research conducted as part of the UK's first longitudinal temperature monitoring study focusing on the 65+ demographic. Data was recorded throughout two heating and two cooling seasons by temperature and humidity sensors. Alongside this, monthly surveys capturing demographic, housing, thermal comfort and health characteristics were disseminated. During the final heating season, interviews were conducted in a subset of the known coldest homes (based on the prior heating seasons results), to identify coping strategies used by older people in maintaining their health and well-being during exposure to low temperatures.

For the heating seasons, older people were found to be comfortable at lower temperatures than guidance recommends, in contrast to outputs of the PMV/PPD model, which significantly underpredicted true comfort. Furthermore, the low temperatures did not seem to adversely affect instances of morbidity and mortality in the sample, however, this could have been influenced by sample size and selection bias. Feelings of comfort were echoed in the interviews, where despite participants recognising their internal temperature could be higher, they felt satisfied.

During the cooling seasons, both the PMV/PPD model and the adaptive model were unable to accurately predict occupant thermal comfort. The study captured a typical and an extreme summer and although, as expected, a larger proportion of the sample were found to be overheating in the extreme summer compared to the typical summer (94% compared to 57%), the majority of self-reported comfort votes fell within acceptable parameters for both summers. Furthermore, instances of morbidity and mortality were not found to be higher in the extreme summer compared to the typical summer.

This thesis demonstrates a disconnect between thermal comfort models and self-reported comfort of older people in both heating and cooling seasons. This has clear implications for under and overheating analysis, since both models' failure in capturing comfort highlights the challenge of safeguarding the ageing population's health within their homes, whilst ensuring over-prediction of comfort does not cause emissions to be increased needlessly through higher than necessary recommended internal temperatures.

Outputs of Research

This thesis incorporates published, accepted (with revisions) and in review papers, as follows:

Paper	Chapter in Thesis	Publication Status
Winter thermal comfort and health in the elderly.	4	In review - Energy Policy Journal
'The older I get, the colder I get' - older people's perspectives on coping in cold homes.	5	Published in Journal of Housing for the Elderly
Summer thermal comfort and overheating in the elderly.	6	Published in Building Services Engineering Research and Technology

Conferences

Hughes, C. and Natarajan, S. 'The elderly and their Indoor Environment: Use of thermal comfort models to determine occupant satisfaction', PLEA 2018 - Smart and Healthy within the 2-degree Limit, Hong Kong, 2018.

Hughes, C. 'UK winter temperatures and the health of the ageing population', UKIEG 2018 Conference - Ventilation, Indoor Air Quality and Human Health, Glasgow, UK, 2018.

Hughes, C. 'How do the elderly heat their homes? Exploring Fuel Poverty and Carbon Reduction in this demographic'. LoLo 2016 Conference - How many ways can you change a lightbulb? Exploring methods in Energy Research, London, UK, 2016

Research Talks

Guest Lecture (45 mins), University of Durham Energy Institute. 'The HAPIE Project - Health and the ageing population's internal environment'. Durham, UK, 2017.

Fuel Poverty Research Network Lightning Talk (5 mins). 'Old and Cold - how cold homes affect the elderly demographic'. Sheffield, UK, 2018.

Public Engagement

Runner up for 'Vice-Chancellors Postgraduate Prize for Public Engagement'. Bath, UK, 2018

Guest Talk (15 mins), Bath Royal Literary and Scientific Institute. 'Home'. Bath, UK, 2017.

Research Objects Talks for Volunteering Team, Bath University (2x10mins). Bath, UK, June 2016 and January 2017.

Pint of Science Festival (10 mins). ‘The true cost of Cold Homes’. Bath, UK, 2017.

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List of Abbreviations

ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers

CERT - Carbon Emission Reduction Target

CERO - Carbon Emission Reduction Obligation

CESP - Community Energy Saving Programme

CIBSE - Chartered Institution of Building Services Engineers

DTM - Dynamic Thermal Modelling

EWD - Excess Winter Death

ECO - Energy Companies Obligation

FIT - Feed In Tariff

HHCRO - Home Heating Cost Reduction Obligation

HVAC - Heating, Ventilation and Air Conditioning

NHS - National Health Service

PMV - Predicted Mean Vote

PPD - Percentage of People Dissatisfied

PHE - Public Health England

RHI - Renewable Heat Incentive

TSV - Thermal Sensation Vote

WHO - World Health Organisation

List of Equations

Chapter 1

Introduction

The UK, along with most of Western Europe, is experiencing a demographic shift towards an ageing population. At present 18% of the total UK population is aged 65 and over (11.8 million people), but in 50 year's time the proportion of 65+ is expected to increase to 26% of the total population (20.4 million people) (Storey 2018). Within this it is the oldest old, ie. the 85+ demographic, that will see the largest increases, with predictions suggesting that in the next 50 years this demographic will treble from a current 2% of the total population (1.6 million people) to 7% of the total population (5.1 million people) (Storey 2018).

Retirement age has not increased commensurately with age and despite more 65 years olds working than ever before, by the age of 65 over 90% of people have retired. Naturally, this results in increased time spent in the home: the average 65 to 84 year old spends 85% of their time at home, which rises to 95% for those aged 85 and above (Hamza and Gilroy 2011). Over the past two decades a growing body of evidence has made the link between buildings and human health increasingly apparent, thus, the importance of ensuring the population lives in healthy and comfortable homes is becoming increasingly significant (Liddell and Morris 2010).

Prolonged exposure to extreme temperatures is believed to adversely affect the health of older people, especially when these extreme temperatures are found in their homes (Donald 2009). As a result of biological ageing, the older a person gets the more their body becomes susceptible to illness associated with extremes of temperature. Sub-optimally heated homes increase the likelihood of cardio and cerebrovascular problems including strokes, pulmonary embolisms and myocardial infections (Crawford et al. 2003), whilst also suppressing the immune system and exacerbating respiratory conditions, rheumatism and arthritis. Prolonged exposure to high temperatures can also cause or exacerbate circulatory and respiratory problems through heat stroke and heat exhaustion, leading to morbidity and mortality (Astrom et al. 2011).

Despite a relatively mild climate, the UK has one of the highest rates of cold-related mortality in Europe (Rudge and Gilchrist 2005), with an average of 25,560 preventable deaths in older people each winter (ONS 2018*a*). By contrast, heat-related mortality is not so severe in the UK and deaths are only prevalent when a heatwave has occurred, for instance the heatwave of 2003 which claimed the lives of over 2000 people in the UK (Johnson et al. 2005). Heatwaves are predicted to become increasingly common in the UK as the climate changes over the next few decades; with warnings that heat-related deaths could be expected to rise by 257% each year by 2050 (Hajat et al. 2013). The ageing population means that ensuring older people live in satisfactory homes that do not detrimentally affect their health is increasingly significant.

Successfully achieving this presents a challenge. Around one third of all UK housing is occupied by over 65 year olds (Pannell et al. 2012), where they are believed to require heating for longer periods than the working age population (Roberts 2008*b*). Thus, older people are believed to struggle the most of any demographic to achieve thermal comfort, which is especially concerning when considering they are some of the most vulnerable to the health effects of inadequately heated and cooled homes (Donald 2009). With an ageing population aiming to reside at home for as long as possible, this could result in a paradoxical situation where the desire to live at home for longer could result in health risks.

At present, it is known that a significant number of older people are suffering morbidity and mortality through inadequately heated and cooled housing, but there are still a number of unknowns. It is not clear what temperatures are achieved in the over 65 demographic, whether people are comfortable at the temperatures they do achieve, what, if anything, precludes them from achieving their desired temperature and what influences them in making decisions about their thermal comfort. Investigating this in the over 65 demographic is key to ensuring that older people are able to stay healthy and comfortable in their homes.

1.1 Overall aim and research questions

The overall aim of this thesis is to create a more comprehensive understanding of what temperatures over 65 year olds achieve in their homes, whether they are comfortable at these temperatures, how their homes affect their health in extremes of temperature and strategies they implement to ensure comfort. This aim is achieved by addressing three research gaps that have been identified in the literature review. These gaps were used to create the following three Research Questions:

1. During winter periods, what internal temperatures are achieved in participating homes, how comfortable are the participants and how effective is Fanger's Predicted Mean Vote (PMV)/ Percentage People Dissatisfied (PPD) model in predicting thermal comfort of homes occupied by over 65 year olds? - This reports data collected from 43 homes over two heating seasons (2016-2017 and 2017-2018) to better understand what temperatures are achieved in homes oc-

cupied by older people, how many participants report being comfortable and at what temperatures and how applicable Fanger's PMV/PPD model is in predicting thermal comfort of the over 65 demographic during low temperatures.

2. What strategies do older people perform to reduce cold-related morbidity and enhance their comfort? - By conducting interviews with a subset of the coldest participating homes, the methods used by older people to stay warm in their homes have been established and discussed.

3. During summer periods, what internal temperatures are achieved, how comfortable are the participants and how effective are Fanger's PMV/PPD model and the adaptive model in predicting thermal comfort during summertime? - This reports data collected from 37 homes over two cooling seasons (summers of 2017 and 2018) to establish what internal temperatures are achieved in summer, how comfortable they are at the achieved temperatures, whether their homes are considered to be overheating and how applicable Fanger's PMV/PPD model and the adaptive model are in predicting thermal comfort of the over 65 demographic during high temperatures.

Each Research Question forms a chapter of the thesis and is discussed further in section 1.2.

1.2 Thesis layout

This thesis is comprised of eight chapters. As this thesis incorporates published, accepted and in review papers, there is some overlap between the content of the literature review and the introductions in chapters 4,5 and 6. This was considered necessary as the literature review enables the topic to be investigated in further detail, but some context of the problem was necessary for each of the papers.

Chapter 2 reviews relevant literature by introducing thermal comfort in the context of older people, Fanger's PMV/PPD and the adaptive models as well as reviewing existing temperature monitoring studies, factors influencing thermal comfort of older people and strategies and policies aimed at supporting them.

Chapter 3 contains the methodology. The research design, participant demographic, location, methods of data collection and pilot study are discussed, as well as the work conducted in comparing the chosen temperature and humidity sensors against the industry standard monitoring equipment.

Chapter 4 presents the first journal paper to be submitted as part of this work, *Thermal comfort and health in the elderly.* This chapter discusses the internal temperatures achieved, comfort vote results and the applicability of Fanger's PMV/PPD thermal comfort model. It proves that the model is not suitable for use in the older demographic and proposes an updated PMVe model for the elderly.

Chapter 5 presents the second paper, *'The older I get, the colder I get' - older people's perspectives on coping in cold homes*, which uses the interviews conducted as part of this project to identify the coping methods used by older people to stay warm in their homes during in periods of cold weather.

Chapter 6 presents the third paper, *Summer thermal comfort and health in the elderly*, which includes summertime internal temperature and comfort results and discusses how applicable Fanger's PMV/PPD model and the adaptive model are during one typical summer and one extreme summer.

Chapter 7 discusses the three papers and highlights the overall findings of the thesis.

Chapter 8 concludes the thesis by summarising the main outputs of the research and identifying the key research contributions of the work, as well as discussing the limitations and recommendations for future work.

Appendicies 1-8 contain Fanger's PMV/PPD equations, demographic and clothing tables, the questionnaires, interview transcripts and recruitment letters..

Chapter 2

Literature Review

Successfully providing for an ageing population is a widely accepted precept of modern society, however, consensus on how best to achieve this is yet to be reached. Recent years have witnesses research efforts intensify, especially on health and housing of older people (Donald 2009). It is generally accepted that most older people wish to 'age in place', whereby they choose to continue occupying their current home for as long as it is feasible to do so (vanHoof et al. 2017), but at present this is not always realistic. Whilst some older people experience good health and maintain physical ability into very old age, others suffer a plethora of chronic illnesses which necessitate a sedentary and home-centric lifestyle (Guy et al. 2015). Clearly, the lived experience of older people differs greatly, so too does their susceptibility to extreme temperatures. Older people are known to spend on average 90% of their time in their homes (Hamza and Gilroy 2011), so it is the home environment where exposure to extreme temperatures can occur. Consequently, it is believed that housing of older people plays a significant role in safeguarding their health and hence, will play a critical part in ensuring the needs of the ageing population can be met.

At present, the relationship between poor housing and poor health is said to be most clearly apparent in older people (Donald 2009). Their especial vulnerability to temperatures outside of the common range, such as cold spells and heatwaves, results in significant morbidity and mortality each year (vanHoof et al. 2017). An average of 26,560 excess winter deaths (EWDs) occur each winter in the over 65 demographic (ONSCensus 2018), of which 30% are estimated to result from cold homes (Braubach et al. 2011). The additional 2000 and 680 deaths caused by the 2003 and 2006 heatwaves respectively (PHE 2018*b*), are predicted to become normal by the 2050s (Murphy et al. 2009). The problem is clearly severe, but very little research has been conducted into the internal temperatures that are achieved within homes occupied by older people, whether the achieved temperatures provide sufficient comfort to maintain health and whether occupants are comfortable at these temperatures. All of which is all hugely important in understanding living conditions of older people, but remains unknown.

This chapter starts by explaining the two main thermal comfort models, Fanger's PMV/PPD model and the adaptive comfort model, in the context of older people. Following this, relevant thermal comfort and temperature monitoring studies are discussed, to provide the context in which this study is set. Finally, the key factors that influence thermal comfort and strategies to help older people attain it are discussed.

2.1 Thermal Comfort Models in the context of Older People

Achieving thermal comfort has always been a basic tenet of human life and survival, but it is only in recent decades that it has received significant research attention. Recognition that individual characteristics play a significant part in thermal comfort and explain why people experience different thermal satisfaction in the same environment has been a major focus of research (Parsons 2002). Such characteristics extend beyond simply personal preference and are said to include age, gender, culture, climate and psychological factors (Nicol and Roaf 2017). Whilst today, it is fully appreciated that indoor thermal comfort can influence health, well-being and safety, how this affects older people in particular is less well understood (Miller et al. 2017). The effect of biological ageing on the body is known to increase the likelihood of adverse health problems manifesting (Adams 2008), especially when older people are exposed to prolonged periods of extreme hot or cold temperatures; as can be the case in their homes. Given their increased vulnerability, it is important to understand the thermal comfort and internal temperatures desired and achieved by older people, yet this remains poorly understood.

2.1.1 Applicability of the models to the older demographic

For the PMV/PPD model, although the standard claims complete validity in residential settings, it is unclear how suitable it is for use in elderly demographics, given the bodily changes that result from ageing not accounted for in the model. Fanger claimed that the level of discomfort a person experiences depends on their thermal load, which he defined as the difference between the internal heat production and the heat loss to the environment of a person kept at a comfortable balance of mean skin temperature, sweat secretion and activity level (Parsons 2002). It is known that biological ageing results in a lower metabolic rate and a higher vasoconstriction rate, meaning that less heat is generated within the body and the heat that is generated is easily lost (Day and Hitchings 2011). Therefore, the thermal load of an older person is likely to be different to a younger person which may suggest Fanger's model may be unsuitable for use in thermal comfort of the elderly.

Meanwhile, although the adaptive model provides more opportunity to change the immediate thermal environment, it too may not be suitable for the elderly. Whilst the simple linear relationship between just the comfort temperature and external temperature enables an easy understanding of the topic, it is said to omit salient physiological and psychological variables which are paramount in the study of thermal comfort (Parsons 2002, Halawa and vanHoof 2012), especially in the case of older people, who are physiologically more vulnerable than younger people (Christensen et al. 2009).

2.1.2 Acceptability categories for the models

Outputs of the two models can be converted into acceptability categories based on the standards: ISO 15251 specifies four categories including one for the elderly whilst ASHRAE 55 specifies a general category with modifications (e.g. for elevated air speeds), but no specific guidance for use with the elderly (Table 2.1).

Table 2.1: Application of current thermal comfort standards to the elderly.

Category	PPD (%)	PMV	t_o **Upper Limit (°C)** ‡	t_o **Lower Limit (°C)** ‡	**Explanation**
I	< 6	$-0.2 < PMV < +0.2$	$0.33t_{rm}+20.8$	$0.33t_{rm}+16.8$	High level of expectation; recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and **elderly persons**.
II*	< 10	$-0.5 < PMV < +0.5$	$0.33t_{rm}+21.8$	$0.33t_{rm}+15.8$	Normal level of expectation and should be used for new buildings and renovations. **Applies to the elderly** as ASHRAE 55 does not provide a separate classification.
III	< 15	$-0.7 < PMV < +0.7$	$0.33t_{rm}+22.8$	$0.33t_{rm}+14.8$	An acceptable, moderate level of expectation and may be used for existing buildings.
IV	> 15	$PMV < -0.7$ or $+0.7 < PMV$			Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.

‡ t_o is the operative temperature
* Category II in EN 15251 (BSI 2007*a*) equates to the general category in ASHRAE 55 (ASHRAE 2013)

2.1.3 Recommended internal temperatures and conditions

Ensuring a temperate internal environment is maintained (above 18°C in Winter and below 26°C in summer) is recommended to protect and maintain occupant health. Given the health problems that manifest more severely in older people as a result of extreme temperatures, it is crucial for them to achieve temperate homes (vanHoof et al. 2017). As a consequence it is believed that older people require higher internal temperatures in winter compared to younger people, so recommended internal temperatures exist, discussed in Section 2.1.3.1. Conversely, there are no indoor temperature recommendations for summer, instead homes are measured against the TM59 overheating metric, which does not make specific age-based recommendations. As it is anticipated that climate change will result in an increasing number of heatwaves, the lack of specific guidance for older people, who are known to be most at risk is potentially concerning.

2.1.3.1 Winter recommended internal temperatures

Specific internal temperature recommendations of 18°C for all rooms, but 20–21°C if occupied by the elderly exist primarily to safeguard the health of older people. Developed in the 1980s by the World Health Organisation (WHO 1987), they have been promoted by the UK Government (Wookey et al. 2014) and Age UK (AgeUK 2018*b*). Given the age of these recommendations, and that the studies informing them are older still, there have been recent discussions questioning their suitability today. Whilst some state that there is clear evidence to support these temperature (Ormandy and Ezratty 2012), others dispute this (Wookey et al. 2014). This controversy reflects the wider problem that the internal environment of older people in relation to thermal comfort and internal temperatures is poorly understood.

2.1.3.2 Summertime overheating Criteria

In contrast to the winter recommended temperatures, which dictate temperatures that should be achieved in the home, the Chartered Institution of Building Services Engineers (CIBSE) TM 59 standard dictates temperatures and durations that should not occur in the home. Although no specific guidance exists for homes with elderly occupants. The TM59 metric provides the most recent criteria to ensure comfort and prevent overheating (CIBSE 2017), based on one of the three criterions in the preceding CIBSE TM52 document (CIBSE 2013) and one in CIBSE Guide A (CIBSE 2018).

For completeness the three TM52 criterions are given below:

1. **Hours of exceedance (H_e) -** This represents the duration of overheating, where:

$$H_e = \Delta T \geq 1°C \tag{2.1}$$

   should not be more than 3% of occupied hours for the months May to September.

2. **Daily Weighted Exceedance (W_e) -** This represents the severity of overheating:

$$W_e = \leq 6 \text{ hours per day} \tag{2.2}$$

   Where, W_e, is given by:

$$H_e = \Sigma H_e \cdot WF \tag{2.3}$$

And, the weighting factor (WF) is given by:

$$\begin{aligned} \mathrm{WF} &= 0 \text{ if } \Delta\mathrm{T}\leq 0 \\ &= \Sigma \mathrm{H_{ey}} \cdot \Delta\mathrm{T} \text{ if } \Delta\mathrm{T} > 0 \end{aligned} \tag{2.4}$$

where $\mathrm{H_{ey}}$ is the number of hours where ΔT is greater than 0.

3. **Upper limit temperature($\mathrm{T_{upp}}$)-** This represents the maximum indoor temperature:

$$\Delta\mathrm{T} = \leq 4°\mathrm{C} \tag{2.5}$$

CIBSE Guide A details another criterion that all occupied rooms should not exceed 26°C for more than 3% of occupied hours. TM 59 combines the criteria to stipulate that for living rooms, kitchens and bedrooms the TM52 Criterion 1 must be met and for bedrooms, between the hours of 10pm and 7am, Guide A must be met.

2.1.4 Section Summary

Older people are believed to be most vulnerable to extreme temperatures found in their homes, the internal conditions of which, at present, are poorly understood. Through thermal comfort prediction by Fanger's PMV/PPD model and the adaptive model understanding of older people's thermal comfort can be gained. However, questions over the accuracy of the modelled results, especially in relation to older people, who are believed to have a different metabolic rate, suggests the models may not be able to accurately predict thermal comfort of older people. At present, this remains unknown, along with internal temperatures, self-reported comfort (referred to as Thermal Sensation Vote (TSV)) and whether old people meet the recommended internal temperatures.

2.2 Thermal Comfort and Temperature Monitoring Studies

In order to gain sufficient data to calculate thermal comfort using the PMV/PPD and adaptive models, either climate chamber experiments or field studies are conducted (Wang et al. 2018). Commonly, they include measurement of some or all of the six PMV/PPD variables, outdoor air temperature and Thermal Sensation Vote (TSV). Achieving thermal comfort requires a balance of psychological, physiological, environmental and architectural confluences at a personal level, and as such has attracted a broad variety of research trajectories. Studies in climate chambers tend to focus on psychological and physiological testing, typically investigating thermal sensation (Bae et al. 2017), thermal preference (Wang et al. 2018, Hwang and Chen 2010, Wong et al. 2009) and adaptation ability (Taylor et al. 1995). Physiologically, studies have investigated the effect of gender (Xiong et al. 2015, Indraganti and Rao 2010, Karjalainen 2012), age (Kenney and Munce 2003, Indraganti and Rao 2010, Wong et al. 2009), and risk to health of thermal environments. In relation to the latter, especially hypothermia (Collins et al. 1977, Collins 1986, Romero-Ortuno et al. 2013), thermoregulatory efficiency (Djongyang et al. 2010, Havenith 2001, Salata et al. 2018), cardiovascular problems (Sartini et al. 2017) and physical performance (Schellen et al. 2010, Hayashi et al. 2017).

Conversley, field studies tend to investigate internal temperatures achieved, how temperatures are influenced by environmental and architectural variables and how temperature itself influences health and well-being. Environmentally, climatic zone has a significant effect on thermal comfort, so many studies have been conducted across the world to identify optimum thermal comfort for that region (Mishra and Ramgopal 2013), these include studies in Australia (Williamson et al. 1991, Cena and de Dear 2001), Africa (Ogbonna and Harris 2008, Taki et al. 1999, Akair and

Banhidi 2007), South America (Andreasi et al. 2010, Tablada et al. 2009), Asia (especially China) (Cao et al. 2016, Liu et al. 2012, Han et al. 2007, Zhang et al. 2010, Jiao et al. 2017) and Europe (Kane et al. 2015, Huebner et al. 2018). With some studies comparing thermal comfort across different continents (Zhang et al. 2017). Architecturally, many building types have been studied including offices, classrooms, retail spaces and domestic homes (Rupp et al. 2015, Schweiker and Wagner 2017).

Discussed in this section are the climate chamber studies that have focused on older people achieving thermal comfort, to identify whether thermal response does change with age. Following this, the temperature monitoring field studies conducted in the UK in winter and summer are discussed.

2.2.1 Older people and thermal comfort

In order to create a thermally comfortable environment it is important to understand the thermal sensitivity, perception and preference of the occupant. As a consequence many climate chamber studies have investigated this in relation to older people, some with specific reference to the influence of age, gender and health, as older people are said to be most vulnerable (Donald 2009).

For many years 20-21°C for living rooms and 18°C for bedrooms has been recommended to ensure comfort of older people (Ormandy and Ezratty 2012), however, there are suggestions that a range of 20-24°C is not warm enough to maintain older people's health (Enomoto-Koshimizu et al. 1997), with studies finding the older people prefer warmer environments (+2°C) than younger people (vanHoof and Hensen 2006*b*). Schellen et al. (2010) found, after exposing eight young people (22-25 years old) and eight old people (67-73 years old) to eight hours at 21.5°C and a further eight hours at 17-25°C results showed that thermal sensation of older people was 0.5 votes lower on the PMV scale than younger people, suggesting that older people prefer higher temperatures. However, the limited sample size of this study indicates that more comprehensive research is necessary. Although, findings of a larger scale study examining thermal acceptance of 384 people aged between 60 and 97 concluded that PMV decreased by one vote for every 23.5 years beyond 60, which further supports the view that older people prefer higher internal temperatures (Wong et al. 2009).

Other studies, however, have not found such distinct differences in preferences of older people and younger people. In fact, some argue that once clothing and metabolic rate are considered older people do not perceive thermal comfort differently to younger people (Cena et al. 1998), although this study later admitted that due to a lower activity level and thus met rate, older people did, in fact, require a higher ambient temperature to ensure comfort. Further studies have also concluded that thermal preference does not differ with age (Collins et al. 1977, Becker and Paciuk 2009, Indraganti and Rao 2010), but some argue that what does narrow is the range of temperatures at which an occupant reports comfort. Hwang and Chen (2010) monitored thermal preference of 87 Taiwanese older people, and concluded that the comfort range of older people was narrower than younger people, which is concurrent with other studies (Peng 2010). Further still, some studies report that thermal preference is, in fact, lower in older people compared to younger people. Natsume et al. (1992) concluded that older people preferred the temperature to be 0.7°C lower than younger people and Bills (2016) found that the PMV neutral temperature was considered warm. However, it is believed that thermal perception decreases with age, which questions the validity of self-reported responses, especially when subjected to low temperatures (Blatteis 2012).

As a consequence of this, it is often recommended that older people maintain constant internal temperatures and do not allow for fluctuations (Chapman 2004), however, in finding that older people frequently alter their thermal comfort through movement, clothing and opening doors, curtains and blinds (Tweed et al. 2015), they appear more capable of altering their environment than literature suggests. Nevertheless, it is crucial to recognise health implications that manifest most readily in older people.

Whilst previously mentioned studies have shown in some cases that thermal preference of older people does not differ compared to younger people, studies show conclusively that their health does. Taylor et al. (1995) investigated the effect of age on internal temperature preference by recruiting older (mean age = 66.9 years, s = 4.1) and younger (mean age = 22.9 years, s = 2.9) participants, the number of which was not mentioned. Participants were subjected to a range of 15-35 °C temperatures and given control to make the climate chamber warmer or cooler when the temperature reached above or below their preferred TSV. Results showed that both groups were able to regulate the climate chamber at a level conducive to health, but the older group were found to have lower skin temperatures although they reported feeling more comfortable than the younger group at extreme temperatures. The authors suggest this could be due to previous exposure to thermal stress and hence a greater degree of acceptance, although it could also be that older people are less able to recognise the effects of extreme temperatures on their bodies. Other studies support this finding. DeGroot and Kenney (2007) and Poehlman et al. (1994) proved that metabolic rate is lower in older people due to a decrease in muscle mass, which other studies have shown can alter vasoconstriction rate (Anderson et al. 1996, van Someren 2007) and explain why older people's skin temperature is similar to younger people's in the corporal region (back and chest) but different in the peripheral areas (calf and hand) (Bae et al. 2017, Hashiguchi et al. 2004). In recent months, recognition that metabolic rate plays a significant role in thermal comfort has meant suggestions for research efforts into improving metabolic rate measurement to better inform models (Luo et al. 2018), with further emphasis on the thermohygrometric perception in older people (Salata et al. 2018).

Further studies have tested the influence of age and gender on thermal sensitivity. Xiong et al. (2015) found that women showed thermal discomfort in cold environments whereas men showed thermal discomfort in warm environments. Rohles and Johnson (1972) partially supports this finding, concluding that older women were warmer than younger women, which is interesting considering much literature discusses how older women suffer the cold the most (Monroe et al. 2007, Day and Hitchings 2011). They found no difference in men.

These thermal sensitivity, perception and preference studies in older people have clearly shown that older people are more thermally sensitive, have a lower metabolic rate than younger people and are consequently more at risk of prolonged extreme temperatures in their homes. Hence, irrespective of whether they prefer similar or lower temperatures than that of younger people, it seems their increased vulnerability makes it necessary for older people to maintain an internal temperature that does not potentially engender health problems.

2.2.2 Temperature monitoring field studies in the UK conducted during winter

Whilst climate chamber experiments are able to investigate the health implications of exposure to extreme temperatures, temperature monitoring field studies are able to measure what temperatures are achieved in peoples homes and hence, the extent and severity of risks to health. Most studies to date focus on working age populations on low incomes or in fuel poverty. The three studies to date that focus exclusively on older people were conducted in the 1970s and so pre-date fuel price increases and widespread central heating and are consequently outdated.

The lack of recent UK temperature monitoring studies in older people to date shows a clear research gap. Older people are known to suffer most from the morbidity and mortality associated with cold homes yet have received the least attention in temperature monitoring studies.

1960s and 1970s: These two decades saw the beginning of temperature monitoring studies. Of the five studies before central heating became widespread three were focused on older people. Collins (1986) took spot measurements in February 1969 of 144 homes all lived in by older people. The study found that living room temperatures ranged between 3°C and 14°C for the older homes in the study, while in the more modern flats it ranged between 9°C and 17°C. A larger study of 1202 older people was conducted in winter 1972 across 100 locations in the UK, this study found that average living room temperatures were 16.2°C (Fox et al. 1973). Five years later in London a study of 47 homes were measured with a mean internal living room temperature of 18.4°C (Collins et al. 1977). Of all the temperature monitoring studies, these are the only three to focus exclusively on older people, which shows concerns over the housing of older people dates back nearly 50 years, however, these studies have limitations. Firstly, they are outdated, changes in heating systems and heating patterns have occurred since the 1970s which means these results are no longer necessarily accurate, but more importantly they only recorded spot measurements so it is not possible to build a picture of the entire winter. Furthermore they were conducted before socio-economic questionnaires became more prevalent alongside temperature monitoring studies, precluding the ability to correlate internal temperatures with personal phenomena.

1980s: The National Field Study of Temperatures conducted by the Building Research Establishment was reported in 1981. Spot measurements were taken in 1000 houses, alongside questionnaires. Results showed that the average temperature was 15.8°C, although the homes with central heating ran 3°C warmer than those without. Other factors known to influence temperature today, such as clothing level, activity and household composition were not collected which means a complete picture cannot be built of the homes (Hunt and Gidman 1978). Another research group, Watson House Research Centre run by British Gas, conducted temperature monitoring to investigate the impact of insulation on internal temperatures. The study involved only 33 homes and found that average internal temperatures of uninsulated homes was 19°C and for the insulated homes it was 20.3°C (Nevrala and Pimbert 1981).

1990s: The very comprehensive English Housing Condition Survey (EHCS) was coordinated in 1992 (although it did include data from between 1986 until 1991) (DOE 1995). This nationwide study involved 25,000 homes and is to date the largest temperature monitoring study conducted. The mean internal living room temperature was 18.6°C. A follow up EHCS in 1996 found average internal temperatures of 18.1°C. The 1996 measurement was the final housing study that incorporated temperature monitoring, so there is no comprehensive data set from EHCS after 1996 (DOE 1996).

2000s: There were a number of large scale temperature monitoring studies in this decade, highlighting the increasing focus on temperature monitoring and thermal comfort. The six largest studies include the National Field Survey of Temperatures, the Carbon Reduction in Buildings (CaRB) project, the Warm Front Study, the 4M project: measurement, modelling, mapping and management, the LARES study and CALEBRE. The Warm Front Study focused on recording living room and bedroom temperatures of 888 low income households over the winters of 2001-02 and 2002-03, where mean internal temperatures of 17.9°C and 15.9°C were found in the living room and bedroom respectively (Oreszczyn 2006). Although this was a large scale study, the focus being purely on low income households potentially limits how reflective the findings are of the entire population. In fact, it is known that low income households are not the most vulnerable to low temperatures (Hajat et al. 2007). The CaRB HES data study monitored the living room and bedroom temperatures of 275 dwellings between July 2007 and February 2008, to collect data about heating sources, heating duration and to compare internal temperatures to modelled assumptions. It recorded mean internal living room temperatures of 18.96°C (Huebner, McMichael, Shipworth, Shipworth, Durand-Daubin and Summerfield 2013*a*, Kelly et al. 2013). It did not collect data relating to the house, tenure or occupancy and therefore lacks the potential to correlate temperatures with social phenomena. The final large-scale significant study, the 4M project, is the most comprehensive of the four main studies. Like the previous studies, it recorded living room and bedroom temperatures in 249 homes on an hourly basis between July 2009 and December 2010, but unlike the other studies, questionnaire surveys were disseminated to collect data about the construction, type and age of the house and the age and income levels of the occupants, which enabled a more extensive picture of UK heating to be established. It recorded that mean internal temperatures were 18.5°C for living rooms and 17.4°C for bedrooms (Kane et al. 2015). Another similar study is the EFUS project, which was commissioned by DCLG as part of the English Housing Survey between 2010 and 2011. The study monitored 635 homes between December 2010 and April 2011 focusing on how many homes are kept at at least 18 °C and the hours per day and night that do achieve this temperature or above. The analysis is compared between over 65 year olds and/or those with a disability against those under 65 with no disability. The study found that the majority of homes do not meet the recommendation and calls for stricter policies on retrofitting to enable homes to be heated to higher temperatures without a negative impact on energy demand (Huebner et al. 2018).

2010s onwards: There are further smaller scale studies that have focused on a particular aspect of heating, including Martin (2010), which sought to establish when heating systems were switched on and off through placing iButton sensors on a radiator in a sample of 68 homes. Another study conducted by Yohanis and Mondol (2010) investigated variations in temperature in a small sample of 25 homes located only in Northern Ireland, finding a variety of internal temperatures, with 14% of homes achieving above 21 °C every day and 3% of homes having an average temperature of below 15 °C. For the homes achieving high temperatures, suggested reasons were either the need for high temperatures for thermal comfort or wasteful behaviour, no reasons were suggested for the low temperatures, although it is possibly due to financial constraints. Further studies use subsets of the CaRB, EFUS, Warm Front and 4M datasets to focus on whether older homes are colder than their newer counterparts and whether this is affected in extreme cold (Hamilton et al. 2017), or how comfortable occupants are in extreme temperatures (Huebner et al. 2018).

Each of the three main datasets reporting on internal temperatures, Warm Front, CaRB HES and 4M evidence similarities in the reported temperature results. The Warm Front data recorded an average living room temperature of 19.1°C and bedroom temperature of 17.0°C; the CaRB HES data reported a living room temperature of 19.0°C and the 4M data measured 18.5°C in the living room and 17.5°C in the bedroom. Drawing from these concordant results it is possible to conclude with reasonable confidence that few UK homes are achieving the World Health Organisation (WHO) recommended internal temperatures (Ormandy and Ezratty 2012). It is unclear, however, whether people are happy at these lower temperatures, whether they desire warmer temperatures but are unable to achieve them, and especially whether the recorded temperatures are representative of older people.

The mean internal living room temperatures of each of the studies discussed in this section are plotted in Figure 2.1, where the weak correlation ($R^2 = 0.24$) shows that temperatures have not been increasing over recent decades. This disputes the notion of recent research that internal temperatures have been increasing in recent decades, in fact, there is no evidence that people want significantly higher temperatures in occupied rooms than in previous decades (Wright 2008).

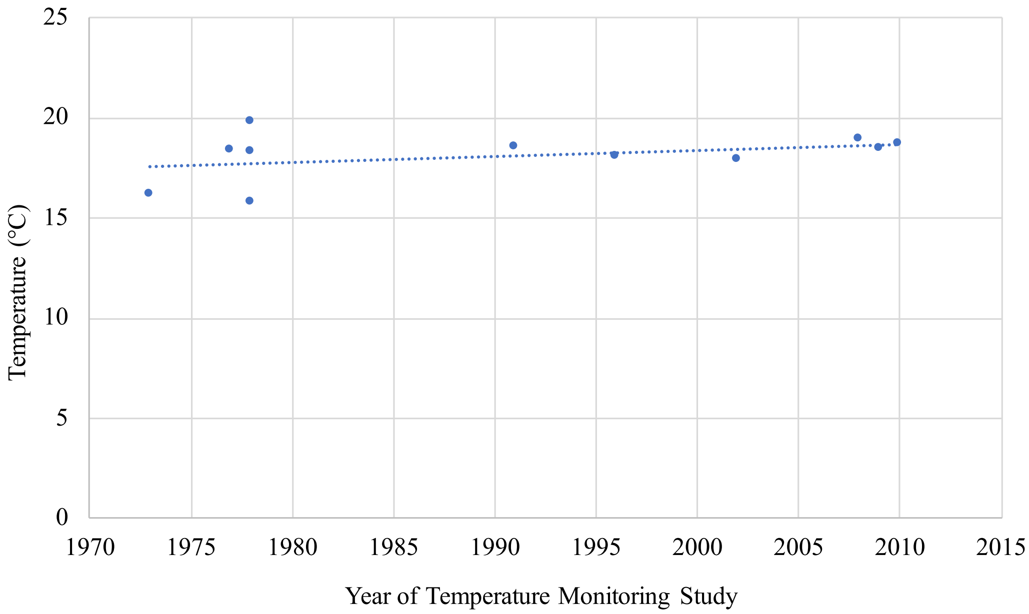

Figure 2.1: Graph showing the mean internal living room temperature for each of the main temperature monitoring studies conducted between 1970 and 2010.

2.2.3 Temperature monitoring field studies in the UK conducted during summer

Summertime temperature monitoring studies are comparatively recent and few. Until the recent more comprehensive understanding of climate change, research efforts centred around temperature monitoring in winter because instances of morbidity and mortality were far greater than for summer. However, recent climate projections suggest heatwaves are expected to becoming increasingly common in coming decades, which will likely result in a greater number of summer morbidity and mortality instances, particularly in vulnerable groups such as the elderly (Hajat et al.

2013). As a consequence, recent research efforts have tended to use dynamic thermal modelling (DTM) to predict potential overheating scenarios based on house morphologies, occupant behaviours and climate change projections (Beizaee et al. 2013). Whilst this is important, there are limitations in that the actions and behaviours of occupants and their attitudes towards ventilation and cooling strategies can never be truthfully modelled. Instead, measurement through field studies can capture this, and prove useful in obtaining data on actual and preferred indoor temperatures. This is especially beneficial for the elderly demographic where a disproportionate rate of morbidity and mortality occurs but little is known about the precise internal temperatures of these homes. The UK summer temperature monitoring studies are discussed in chronological order, as follows:

2000s: The first summer temperature monitoring study was conducted in the summer of 2005 in Milton Keynes, UK. This study found lower than average mean internal temperatures of 19.8°C in the living room and 19.3 °C in the bedroom (Summerfield et al. 2007). Although, the small sample size of 15 homes means that caution is necessary in assuming this is reflective of the wider population. A larger study of 207 homes across England was conducted in summer 2007, where higher mean internal temperatures were recorded (21.8 °C in the living room and 21.6 °C in the bedroom). This study was the first to asses their data against the Guide A and BS EN ISO 15251 metrics, finding that homes were uncomfortably cool, especially detached and pre-1919 homes (Beizaee et al. 2013). A further large study of 230 homes, all located in Leicester, found broadly similar mean internal temperatures as the previous study of 22.2 °C in the living room and 22.4 °C in the bedroom. They didn't however, assess any overheating metrics. Meanwhile, Pathan et al. (2017) measured 122 London homes in the summers of 2009 and 2010 against the ASHRAE 55 standard, where conclusions showed that the studied dwellings had a significant risk of overheating in the current climate.

2010s: This decade saw further studies, on a much smaller scale. Over the summers of 2011, 12 and 13, Sameni et al. (2015) monitored 25 homes in Coventry, UK against the TM52 overheating criteria, where conclusions found that over two thirds of the homes failed the criteria. A subsequent study also measured six homes against TM52 and Guide A (Gupta and Kapsali 2016) and another looked at three homes and measured against Guide A and BS EN ISO 15251 (Jones et al. 2013), both studies found optimal temperatures of 24 °C and as such concluded that overheating is a significant risk. Although the small sample sizes in both studies raises concerns over their representativeness. A further study monitored 20 homes in Leeds (Baborska-Narozny et al. 2015) and another monitored 46 homes in Exeter (Vellei et al. 2016), finding relatively high mean internal temperatures of 23.45°C and 23.9 °C respectively.

2.2.4 Section Summary

There have been a small number of climate chamber studies focusing on thermal health of older people and temperature monitoring field studies to date in the UK. The climate chamber studies have shown that older people are less able to maintain core body temperature at extreme temperatures due to a lower metabolic rate than younger people so have a greater risk to health of exposure to prolonged extreme temperatures in their homes. Meanwhile, temperature monitoring studies indicate that for winter homes are not achieving recommended temperatures and for summer a significant number of homes are overheating. These studies have been conducted in working age populations, who are known to be more resilient than older people. Hence, there is a clear need to identify the internal temperatures and thermal comfort of older people. Despite this, as yet a study into their internal conditions has not been conducted. This research aims to resolve this by conducting the first longitudinal temperature monitoring study of older people in the UK.

2.3 Factors affecting Thermal Comfort of Older People

Thermal comfort can be influenced by a number of factors, discussed in this section. Especially thermal comfort in winter, where the requirement for fuel for heating systems can cause financial concerns for older people, particularly when coupled with an inefficient home.

2.3.1 House condition, maintenance and efficiency

It is common for over 65 year olds to own older properties with outdated heating systems, single glazing and no insulation (Hamza and Gilroy 2011). In fact, at the time of the last investigation (2012) one fifth of older people occupied homes that failed to meet the decent housing standard criteria of meeting the current statutory minimum standard for housing, being in a reasonable condition, having reasonably modern facilities and services and providing a reasonable degree of thermal comfort (Garrett and Burris 2015).

The UK has the oldest housing stock in Europe (Moran et al. 2014) and as the age of a building is strongly correlated with inefficiency the UK has some of the least efficient homes in Europe (Kaveha et al. 2018). Inefficient homes result in significant heat loss, so more fuel is required to keep a home at a comfortable and stable temperature in comparison to a well insulated home. Literature suggests that older people are less inclined to install measures that could improve the efficiency of their homes (Claudy et al. 2010, Mahapatra and Gustavsson 2008, Willis et al. 2011), which suggests they might be living in some of the more inefficient homes.

By 2050 the number of households with occupants aged 65 and over is expected to increase by almost 20%, three quarters of whom are predicted to be owner-occupiers (Pannell et al. 2012), which indicates that we may observe more older people struggling in poor quality housing which, in turn, is likely to cause increases in the levels of morbidity and mortality due to extreme temperatures in homes. This is worrying as poor quality housing occupied by older people increases psychological distress (Committees 2018), the instances of EWDs and costs the National Health Serice (NHS) £634 million every year (Garrett and Burris 2015).

2.3.2 Energy Prices and Consumption

Fuel prices can cause problems for older people as it is widely believed that older people have a higher than average energy consumption because of sedentary lifestyles and long periods spent at home, which require longer heating periods (Roberts 2008*a*), however often older people make severe compromises to achieve thermal comfort (Day and Hitchings 2011). In extreme situations this can mean deciding between food and heating (O'Neill et al. 2006*a*).

Furthermore, recent decades have seen a shift towards smaller households. This is important because whilst larger households tend to use more energy overall, energy use per person increases with decreasing household size (Wright 2008). This is because although larger households tend to have larger homes, each household needs a certain number of appliances and rooms need to be heated to a comfortable temperature irrespective of the number of occupants. As the population ages, it is expected that there will be an increasing number of single person households, especially as one or other spouse dies and the other is left in their home.

2.3.3 Fuel Poverty

Fuel poverty was recognised as an endemic problem in the UK in the 1970s as 'any household that was unable to obtain adequate warmth for 10% of its income' (Boardman 2010). This definition went on to become widely used in policy and in alleviation strategies until 2012, where as an increasing body of fuel poverty research emerged in the 2000s, it became clear that basing fuel poverty solely on the 10% affordability threshold omitted the complex relationship between dwelling efficiency, income, behavioural characteristics and access to fuel; all of which influence the likelihood of a household to be in fuel poverty (Shortt and Rugkasa 2007). Consequently, in 2012 Professor Hills created the Low Income High Cost (LHIC) indicator, which was adopted into policy at the time by the Department of Energy and Climate Change and is still favoured by Government today, despite criticism that it is an 'opaque instrument' requiring substantial amounts of building and occupant information to accurately assess whether a household is in fuel poverty (Burlinson et al. 2018).

Under this new definition a household is considered fuel poor if it has lower than average income and higher than average fuel costs. It is estimated that 37% of older people living alone are fuel poor and 20% of homes with two occupants aged 65 or over are fuel poor (Wright 2004).

2.3.4 Habits and Patterns of Behaviour

Another way in which occupants are claimed to influence heating demand is through their habits and patterns of behaviour. Many habits, such as putting on a jumper instead of turning up the heating, or using hot water bottles, indirectly affect energy consumption and internal temperatures. Attempting to change habits and patterns of behaviour is often thought to be more of a challenge in the older demographic, as older people are perceived as being set in their ways and less capable of adapting to change compared to younger people (Wright 2004, Harrington 2005).

Furthermore, another behavioural factor in which older people are perceived to be out-of-date is in relation to understanding their heating system. It is known that programmable thermostats can reduce energy consumption by 30% for space heating, but these potential savings remain potential unless the occupant actually understands how to use the system (Huebner, McMichael, Shipworth, Shipworth, Durand-Daubin and Summerfield 2013*a*). As older people did not grow up with technology, it is often assumed that they are the least capable at understanding how to use it, this theory extends to their heating system, where it is perceived that they will not understand how to use it to ensure it runs most efficiently (Devine-Wright et al. 2014, Day and Hitchings 2011).

2.3.5 Section Summary

Generally, older people are believed to require more energy than younger people as they are at home for longer periods, for some older people affording the fuel for sufficient heating is not possible, leading to concerns over their health and well-being. Meanwhile, it is also recognised that older people's habits are not necessarily helpful in ensuring they achieve thermal comfort. There is a clear need to understand more about how these factors influence the ability of older people to heat their homes and to what extent older people's attitudes do influence their heating and their thermal comfort. As an increasing number of older people are expected to become owner occupiers in coming years, the problem is likely to worsen.

2.4 Strategies to enable older people to achieve thermal comfort

There are certain policies and aids in place that aim to mitigate older people suffering excessively warm or cold homes, including financial payments, home improvement schemes and guidance and policy documentation.

2.4.1 Financial Assistance

Older people are eligible for a small number of payments to supplement their income and enable them to afford fuel for more heating. The most extensive of these is the Winter Fuel Payment, which is a direct payment of between £100 and £300 to anyone living in the UK aged 65 and over, irrespective of income. Although there is evidence to suggest that since the Winter Fuel Payment was introduced the association between low external temperature and mortality has reduced (Armstrong et al. 2017), critics of the payment argue that because only 20% of the Winter Fuel Payment actually goes to households that do struggle to afford heating (Boardman 2010), essentially £2.6 billion is wasted each year. Instead, they argue, more should be done to target those on low incomes or in fuel poverty, instead of simply supplementing affluent pensioners who have no real need for the money. Another option, not exclusively for older people, but often taken up by them is the Warm Home Discount which provides a reduction in energy bills of up to £140 depending on exact circumstances, although only those who have low incomes or pension credit are eligible. Additionally, should the temperature decrease to 0°C or lower for a week or longer then anyone in receipt of pension credit or benefits can receive the Cold Weather Payment of up to £25 per day for the duration of the cold spell (Government 2018).

2.4.2 Home Improvement Schemes

By retrofitting homes, through fabric upgrades such as insulation and double glazing, the demand for fuel is reduced whilst the same internal temperature as pre-retrofit is achieved. Over the past 15 years the UK Government has introduced a number of financial incentives to entice people to retrofit their homes. The following are not exclusively for older people, but they were able to apply for the grants.

2.4.2.1 Retrofitting Incentives

In recent years the UK Government has introduced a number of retrofit schemes, including Warm Front, Carbon Emissions Reduction Target (CERT), Community Energy Saving Programme (CESP) and the Green Deal, with varied success. The largest, Warm Front Scheme, funded the upgrade of 600,000 homes. Whilst health and well-being benefits were said to be apparent in participating homes (Critchley et al. 2007, Hong et al. 2006), criticism arose, with claims that the scheme did not effectively target the fuel poor, despite having home and occupant information (Hutchinson et al. 2006). Following this, CERT and CESP placed the emphasis on energy suppliers to fund individual house retrofits for the most vulnerable, latterly this has been somewhat subsumed into the Energy Companies Obligation (ECO) Scheme (discussed further in Section 2.4.2.2).

The Green Deal was launched with much publicity in October 2012. It acted as a financing scheme for retrofits, with capital raised from banks, businesses and local authorities who recouped their initial investment through an additional charge on the energy bills of participating homes. The 'Golden Rule' was that the anticipated financial savings from the reduced energy consumption as a result of the retrofit must have been equal to or greater than the cost of carrying out the retrofit (Jones et al. 2013). However, in practice this was not always the case, which resulted in widespread criticism of the Green Deal. Uptake was not as extensive as anticipated, mostly because homeowners were sceptical about how long term the energy saving would be (Dowson et al. 2012).

Whilst policies have instigated retrofit schemes to reduce energy consumption and improve thermal comfort in winter, it is important to recognise that this can have a negative impact on summer conditions. Studies suggest that whilst retrofitting would enable significant reductions in EWDs, it might lead to an increase in heat related mortality of between 1 and 14% (Taylor et al. 2018). This is an important consideration in light of potential future climate change scenarios.

2.4.2.2 Energy Generation Incentives

Schemes such as the Renewable Heat Incentive (RHI), involved homeowners being paid per unit of energy for producing heat from a renewable source and using it for their domestic space heating (Snape et al. 2015). Similarly, the Feed in Tariff (FIT), gave money for energy fed back into the grid generated by renewable technologies. These schemes have come under scrutiny for altering the tariff payback rates, making the schemes less lucrative for homeowners (Walters and Walsh 2011).

A further subsidy available through the Energy Companies Obligation (ECO), was created five years ago to address two key areas, the first is the Carbon Emissions Reduction Obligation (CERO), requiring energy suppliers to promote energy efficiency measures such as insulation and new boilers and the other is the Home Heating Cost Reduction Obligation (HHCRO), obligating energy suppliers to promote and provide assistance to vulnerable households who are at risk of fuel poverty. Companies can choose which homes they treat and how much to fund, with the carbon and cost savings of these measures counting towards the companies' obligations.

2.4.2.3 Rebound Effect

Generally, the home improvement and energy generation incentives aim to reduce energy consumption in an attempt to achieve the Climate Change Act 2008 stipulation that the UK must reduce emissions by 80% by 2050 on baseline 1990 levels (Climate-Change-Act 2008). However, the rebound effect is commonly observed, whereby energy consumption increases post-retrofit as occupiers decide to improve their thermal environment and comfort for the same amount of energy they used previously, as opposed to achieving the same thermal environment but using less energy. Although viewed as a problem, this can be beneficial in the case of older people who, post-retrofit, are able to achieve a level of comfort that prevents health problems.

2.4.3 Guidance and Policy

The UK Government produces the Cold Weather Plan for England (PHE 2018*a*), and the Heatwave Plan (PHE 2018*b*), aimed at those working in health and social care who are likely to come into contact with people vulnerable to the effects of the cold and hot temperatures, including older people. The plans details strategies for identifying and supporting people who are most at risk of the morbidity and mortality associated with cold and hot homes.

There are further guidance documents produced by organisations including, but not limited to, Age UK, the National Institute on Ageing, the NHS and the British Geriatric Society. All suggest methods to stay warm and healthy during cold weather including using hot water bottles, blankets and wearing many layers (AgeUK 2018*b*). Whilst for summer they suggest drinking plenty, staying out of the heat between 11am and 3pm and closing curtains in the daytime (AgeUK 2018*a*).

2.4.4 Section Summary

There are a small number of financial aids and incentives aimed to help older people to afford sufficient heating to achieve thermal comfort, however, many of the schemes face criticism. Financial incentives are said to not target those most in need of assistance, with the majority of the Winter Fuel Payment being wasted. Furthermore, retrofitting and energy generation incentives have been lambasted for not providing the promised financial gains and not targeting the efficiency measures sufficiently well to ensure those most in need benefit. Moreover, although the guidance and policy documentation is extensive, it is basic and likely to be considered common sense by many older people.

2.5 Chapter Summary

Most older people are known to want to age in place, however this raises concerns over the suitability of their homes as they age. It is said that older people suffer the most from the cardiovascular and respiratory problems that are known to occur in the most vulnerable members of society when exposed to extreme temperatures. Older people are known to spend in excess of 90% of their time in their homes which necessitates a better understanding of their internal environment. At present, their increased vulnerability is known, but the internal conditions of their homes are not, leading to the suggestion that sub-optimally heated and overheated homes are causing and exacerbating health problems. It is clear a better understanding of their thermal comfort and internal temperatures is necessary.

Use of Fangers PMV/PPD and the adaptive model are the methods commonly used to predict thermal comfort. However, it is unclear how applicable they are to the older demographic, with critics suggesting that the variables necessary are not able to be accurately measured, especially metabolic rate, which is believed to differ for older people in comparison to younger people. Furthermore, it is unclear to what extent older people meet the winter and summer recommended thermal conditions. At present, there has been no research conducted into this, so a research gap is clear, which this thesis seeks to address.

Thermal comfort studies are few, and the ones involving older people fewer still, despite recognition that inadequate thermal environments and thus thermal discomfort lead to poor health. Existing studies show no cohesion in their results, which highlights the poorly understood nature of thermal comfort in older people. Temperature monitoring studies show that UK homes do not seem to be achieving the WHO recommended temps, although actual levels of discomfort are unclear. This raises the question, especially in older people, of how aware they are of their environment.

There are certain monetary aids, aimed to alleviate some suffering, however these are said to be poorly targeted and executed. Therefore, it is clear that although there is widespread recognition that older people suffer due to excessively cold or hot homes, the condition of their homes remains unclear. The temperatures that older people endure are unknown, and it is unclear whether they are comfortable at these temperatures, if not then why not and if they are comfortable are these temperatures conducive to good health. Answers to these questions are necessary to enable a better understanding of thermal comfort in the elderly.

Chapter 3

Methodology

This study is the first longitudinal temperature monitoring study to focus exclusively on the over 65 demographic in the UK. A number of possible research designs were considered before deciding on the method chosen.

A possible method for the study would have been a transverse, as opposed to longitudinal, data collection method. The transverse method involves taking spot temperature measurements in each participating home, which typically enables a larger sample size than longitudinal studies, because the sensors are not required for long durations in each home and so can be used for more than one home. Whilst having data from a wider sample can be beneficial, the strength of having only one measurement per home in comparison to thousands of measurements through longitudinal monitoring was not considered to be beneficial enough. Instead, it was decided that longitudinal monitoring enables a much more detailed temperature profile of each home to be made, as well as the ability to follow the same set of participants over a two year period, capturing large amounts of data.

An alternative possibility would have been to recruit participants for a laboratory based study. Whilst this would have enabled understanding of what internal conditions the participants find comfortable, it would not have enabled measurement of their homes. It was decided that it is better to understand what temperatures people are achieving in their homes and whether they feel comfortable at these temperatures rather than simply what temperatures older people do feel comfortable at.

A further possible design would have been to have a sample of over 65 year olds and a sample of under 65 year olds to compare the findings of both. There are already extensive studies into the thermal comfort of working age populations so it was decided that focusing all attentions on over 65 year olds would enable more 65 years and over participants enabling a greater breadth of understanding of their internal environment.

Therefore, the longitudinal temperature monitoring of exclusively 65 years and over was decided and is discussed further below.

3.1 Research Design

Through conducting a longitudinal temperature monitoring study exclusively in the over 65 demographic this research aimed to create a better understanding of how the over 65s heat their homes, what temperatures they achieve, what temperatures they would like to achieve and if they are not achieving their desired temperature, then why not.

This research aimed to answer these questions by placing temperature and humidity sensors in participating homes for 24 months over two heating and two cooling seasons. There were four phases of data collection:

Table 3.1: Phases of the project

	November - March	June - September
2016 - 17	Phase 1	Phase 2
2017 - 18	Phase 3	Phase 4

3.2 Location

The study was conducted in the city of Bath, South-West UK. The City of Bath is designated as a UNESCO World Heritage Site and is famed for its Georgian buildings, built in the 18th Century. Nationally, the number of pre-1919 buildings represents 21.5% of the total stock, but this rises to 30% in Bath (Moran, 2012). Buildings of this age often pose complex challenges in light of the increasing emphasis on emissions reductions. These houses are built with solid walls and single glazing and frequently legal protection precludes any modernisation. This makes Bath an ideal location for the study. A secondary effect of studying such homes is the possibility of participants suffering fuel poverty. Whilst this study did not set out to exclusively study those in fuel poverty, it was appreciated that this may occur as a result of this type of work, as the literature showed the link between older buildings, older people and the likelihood of fuel poverty. Figure 3.1 shows the City of Bath marked with the 16 wards.

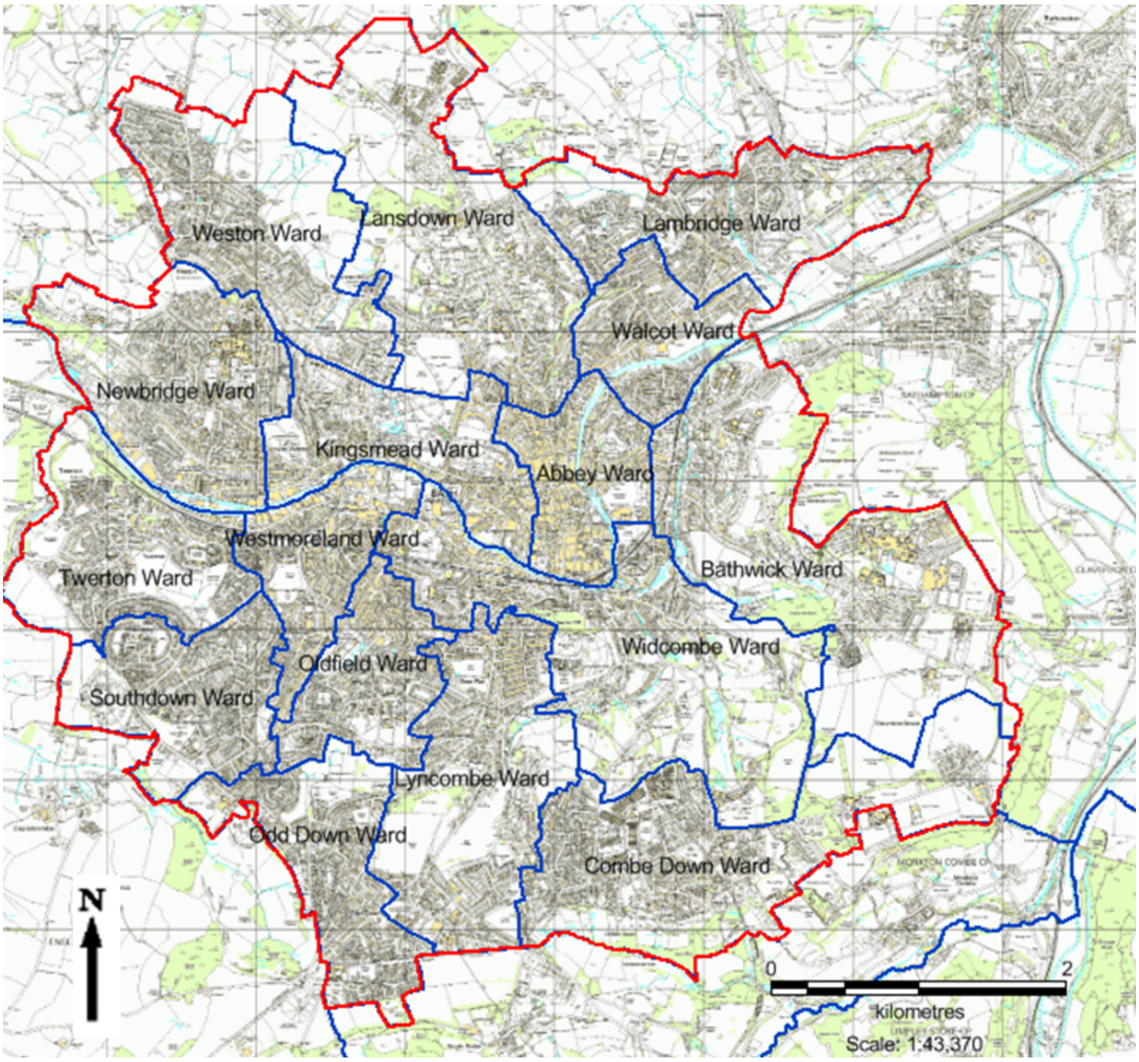

Figure 3.1: Map of Bath with the 16 wards of Bath marked and named, reproduced from Ordnance Survey Map of Bath and produced by Research and Intelligence Team Bath and North East Somerset Council (2015).

3.3 Participant Recruitment

The only requirement to participate in the project was to be aged 65 years or over. Figure 3.2 shows that Weston (24.04%), Combe Down (19.76%), and Lyncombe (19.47%) had the highest proportion of people aged 65 years and older, and were the only three wards to have a higher proportion than the BANES average of 18.08%. Nine of the sixteen wards had a higher proportion of older people than the UK average of 16.45%. Walcot (10.91%) and Westmoreland (11.13%) had the lowest proportion of people aged 65 and above.

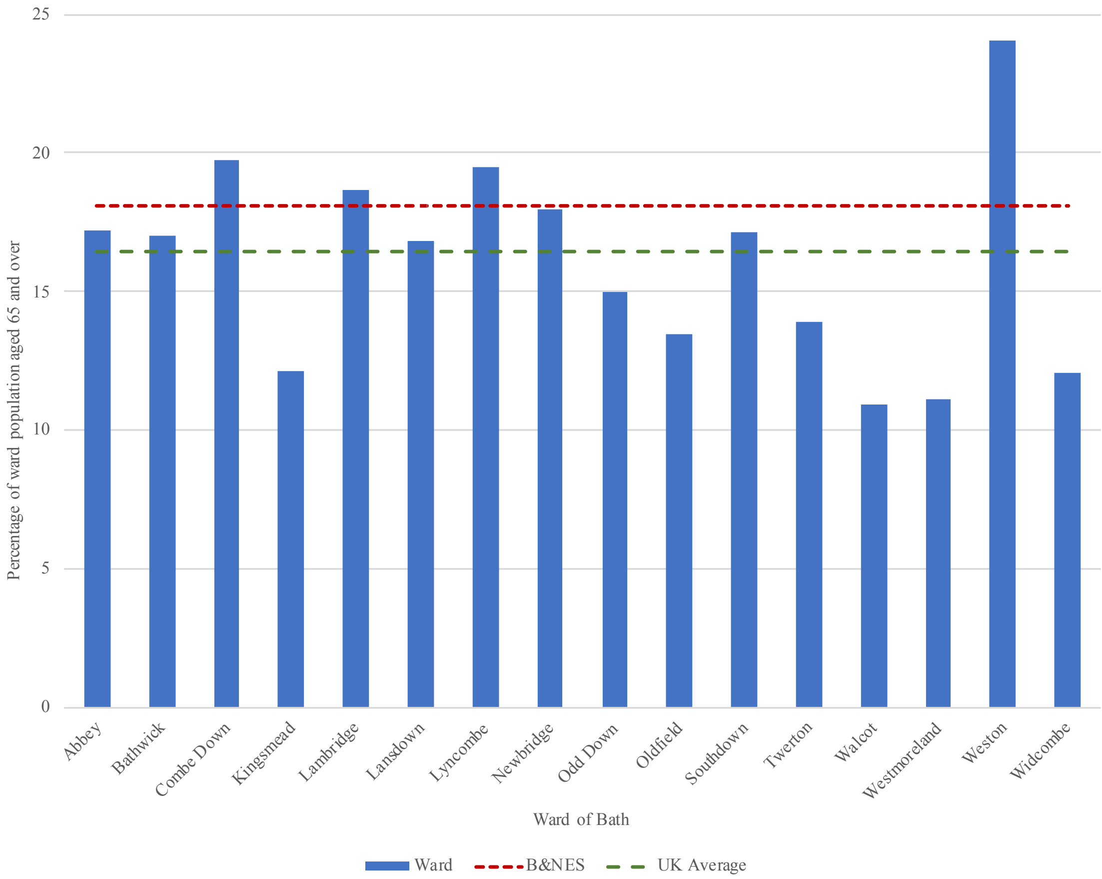

Figure 3.2: Percentage of people aged 65 and over living in each ward of Bath, with Bath and North East Somerset average (red dotted line) and UK average (green dashed line). (Bath and North East Somerset Council, 2015).

As with the national population, the number of older people in Bath is expected to rise over the next few years. As can be seen in Figure 3.3, it is the octogenarian and nonagenarian age categories that are expected to see the greatest increases of up to 53%, therefore Bath is likely to encounter more older people living independently in the near future.

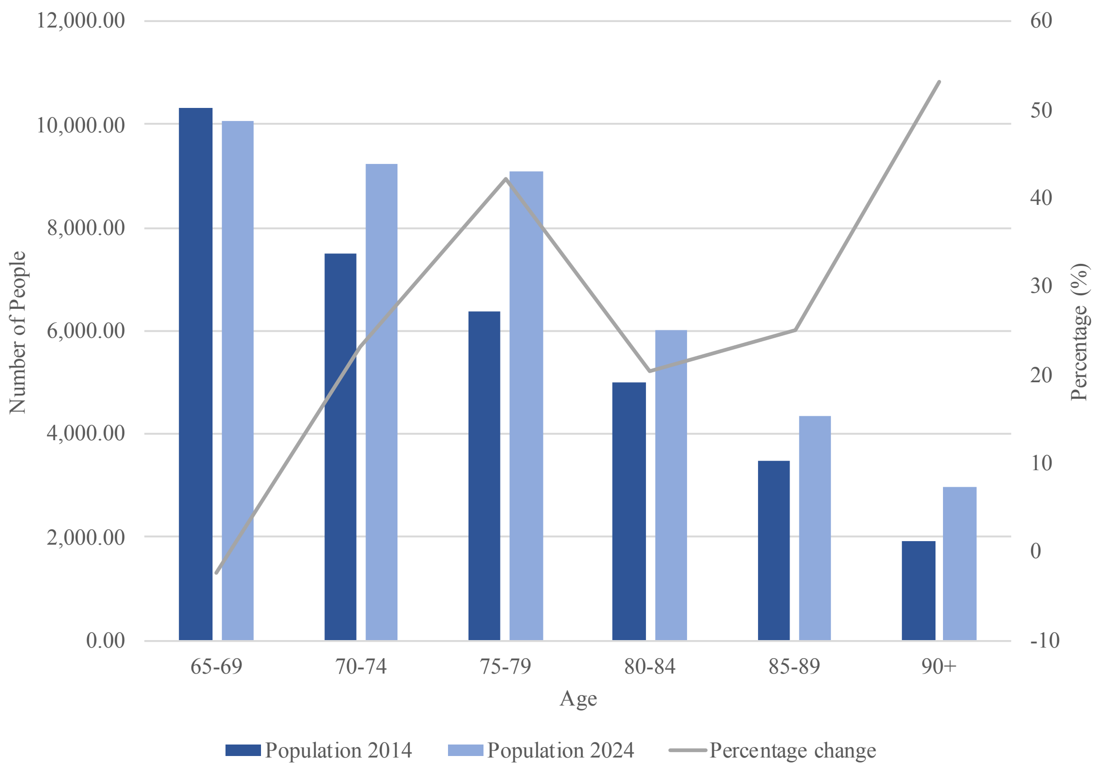

Figure 3.3: Number of people aged 65 and over living in Bath in 2014 compared to the number of people aged 65 and over predicted to live in Bath in 2024 and the percentage change over that decade for each of the age classifications. (Bath and North East Somerset Council, 2015).

In order to gain a sample of people aged 65 and over for the project, two methods of recruiting participants were used:

- *Random sampling*: In order to minimise bias in the sample, a random sampling process was adopted. Fourteen areas of Bath were selected (all except Walcot and Westmoreland), with two or three streets in each area targeted for the letters (explained further below, but fully shown in appendix 8) to be posted. Six hundred letters were posted in total through this process. Households expressing interest were either emailed further information (another 1 page letter detailing more information about timescales and project phases, also shown in appendix 8) or phone called, depending on their preference.
- *Targeted sampling*: To increase the likelihood of reaching an older demo-

graphic, presentations were undertaken to groups such as Age UK, University of the Third Age, Lunch Clubs and St. John's Care, in Bath. Each presentation lasted 30 minutes, followed by another 30 minutes of Q&A, with the chance to ask questions individually. Interested members of the audience were provided a letter incorporating the briefing letter and the further information letter as in the random sampling.

The participant recruitment letter informed potential participants (i) of the aims of the study, (ii) that temperature sensors would be placed in their home during the phases of the study, (iii) that they would be asked to answer thermal comfort and health questionnaires on a montly basis

Through random sampling 25 participants were recruited (4.2% response rate) and through the targeted sampling a further 18 were recruited bringing the study total to 43 participating homes with a total of 59 occupants. Each home designated one person to respond to the surveys to ensure continuity. Figure 3.4 shows the range of wards participants lived in and the proportion of participants there.

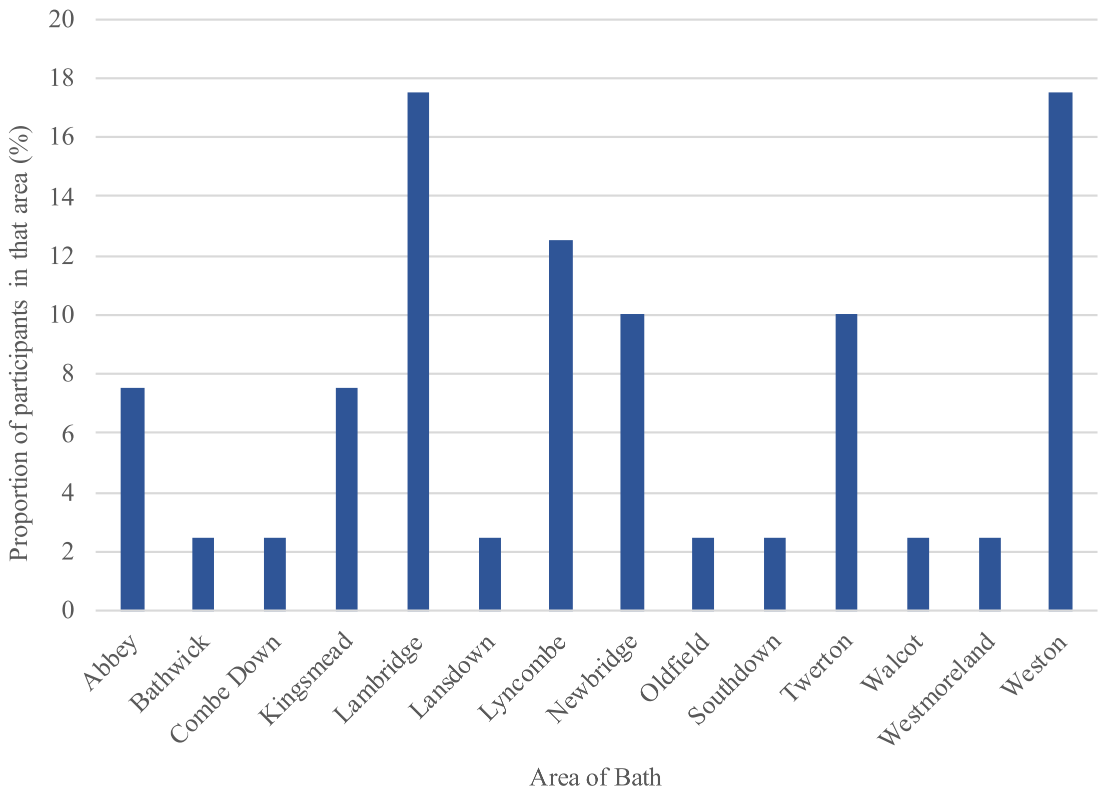

Figure 3.4: Chart showing the proportion of participants living in each ward.

3.4 Methods of data collection

Both qualitative and quantitative data collection methods have been used in the study. Both are described further below.

3.4.1 Quantitative Data - Temperature and Humidity Sensors

In order to measure the temperature and humidity in the participating homes, iButton and HOBO sensors were compared, as these are the two most frequently used sensor types in similar studies (Kane et al. 2015, Huebner, McMichael, Shipworth, Shipworth, Durand-Daubin and Summerfield 2013*a*). After comparison, the iButton sensors were chosen, discussed below.

3.4.1.1 iButton DS1922L-F5

The iButton sensor contains a computer chip within a stainless steel container, with a diameter of 16mm and height of 5mm, as shown in Figure 3.5. The chip records temperatures between -40°C to +85°C at pre-determined intervals of between 1 second and 273 hours. A total of 4096 readings can be taken and stored in the memory. These sensors are small, resistant to dirt and moisture and can easily be mounted on a variety of surfaces.

Figure 3.5: Maxim's iButton DS1922L-F5 Temperature Sensor

3.4.1.2 HOBO UA-001-08

The HOBO UA-001-08 sensor is larger than the iButton sensor, as can be seen in Figure 3.6. The internal chip records temperatures between -20°C and +70°C at user defined intervals of between 1 second and 18 hours. A total of 6500 measurements can be taken and stored in the sensor's memory. Being larger and pendant shaped, the HOBO sensor is more difficult to mount onto surfaces and is more obtrusive than the iButton.

Figure 3.6: HOBO UA-001-08 Temperature Sensor

3.4.1.3 Sensor Calibration

A sensor selection test was undertaken to compare results of each sensor and decide which type to purchase for the study. Use of a climate chamber enabled certain parameters to be set, replicating real world exposure. The chamber was programmed to reach a high temperature of 35°C and a low temperature of 5°C every 30 minutes, with relative humidity set at 50%, over a 6 hour period. Figure 3.7 shows that the iButton sensors recorded temperatures between 6°C and 36°C, spanning the full 30°C at 1°C out, which is within the accuracy of the sensors. Whereas the HOBO sensors spanned a temperature range of 25°C, between 8°C and 33°C. Consequently, the iButton sensors were chosen for the study as they spanned the full temperature range.

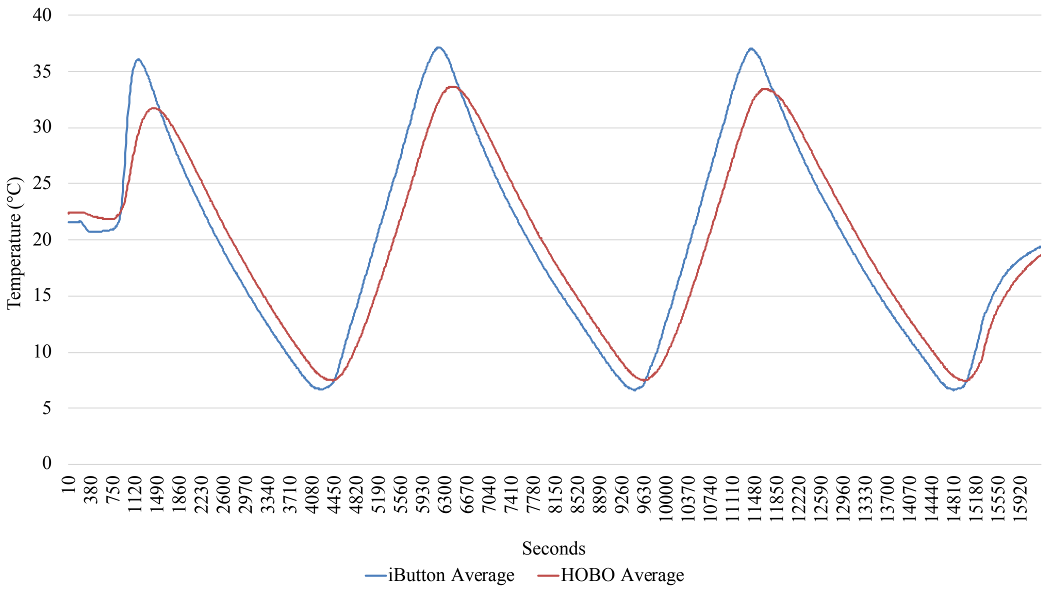

Figure 3.7: Climate Chamber test comparing HOBO UA-001-08 Temperature sensor with iButton DS1922L-F5 Temperature sensors, between temperatures of 5°C and 35°C at 50% relative humidity.

The iButton sensors were further tested over a seven hour period with the temperature spanning between 16°C and 26°C every 30 minutes. Results from the test are shown in Figure 3.8.

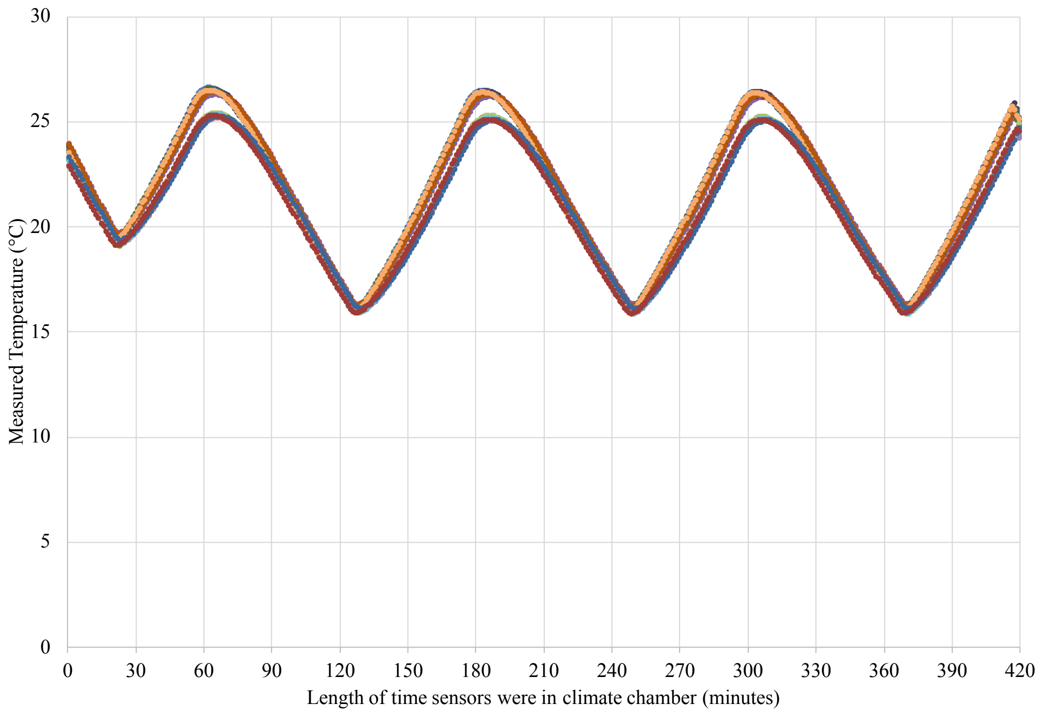

Figure 3.8: Climate Chamber test measuring iButton DS1922L-F5 Temperature sensors, between temperatures of 16°C and 26°C at 50% relative humidity.

3.4.1.4 Sensor Placement in Homes

An average household spends approximately 90% of their time in either their living room or bedroom (Hoppe and Martinac 1998). Consequently, these were the two rooms chosen to locate the sensors. As the aim was to measure internal temperatures, it was also important to determine to what extent the measured temperatures resulted from the heating system being switched on. Therefore, three sensors were placed in each home:

1. Living Room sensor - placed in the living room to record air temperature.
2. Radiator Sensor - also placed in the living room, on the radiator, as shown in Figure 3.9 to measure when the heating system was switched on and off.
3. Bedroom Sensor - placed in the main bedroom to record air temperature.

Figure 3.9: Method of attaching the radiator sensor to the radiator. Insulation pipe, cut to 5cm, with small indent for sensor to fit was taped around the pipework on the radiator.

Care was taken to ensure that they were not placed near windows, doors or radiators and fires to avoid any incorrect temperature readings and all were placed as close to 1.5m above the floor level as possible as shown in Figure 3.10.

Figure 3.10: Typical placement of sensors within homes.

3.4.1.5 Sensor quality and lifetime

The lifespan of the sensors was considered before the study commenced to ensure that they would retain enough battery power for the duration of the study. The manufacturer's details state that the anticipated lifetime of the sensor is approximately 3.5 years for the temperature range of 15-30°C, which was the temperature range expected to be recorded for the study. Three and a half years clearly exceeded the duration of the study, mitigating any concerns over battery life expiring part way through the project. Furthermore, there is very minimal time drift of the real time clock of the DS1922L-F5 at the temperature range anticipated in the study (15-30°C).

3.4.2 Qualitative Data - Questionnaires and Interviews

Both questionnaires and interviews were used to collect socio-economic information about the participants. Each are discussed in more detail below.

3.4.2.1 Questionnaire questions and structure

There were two questionnaires in the project, both designed to gain more information about occupant health, wealth, heating systems and attitudes towards heating. The first was a comprehensive survey, answered at the beginning of phase one, designed to provide a thorough demographic profile of each participant and to provide information about housing characteristics, thermal comfort, heating and health. This questionnaire was split into eight sections:

1. *Household characteristics*: Intended to gain a profile of each participant including age, gender, educational attainment, income and housing fabric.
2. *Temperature*: Intended to find out how comfortable participants felt.

3. *Air movement*: Intended to ascertain the amount of air movement within the home and whether this affected the participants.

4. *Moisture levels*: Intended to ascertain whether there was any condensation, mould and damp in the participating homes, and if so, whether this affected the participants.

5. *Heating*: Intended to find out how much the participants knew about their heating system and how they used it.

6. *Health*: Intended to find out how many participants suffered from chronic illnesses and whether they were illnesses that could be worsened by extreme temperatures.

7. *Clothing*: Intended to ascertain how many layers of clothing people wore to feel comfortable.

8. *Attitudes towards the environment*: Intended to gain an idea of whether people's environmental attitude affected their use of heating.

The second questionnaire was much shorter and was answered monthly throughout the project phases with the aim of capturing changes in thermal comfort and health, so questions included perceived level of thermal comfort, actions people took to keep warm or cool and whether any health complaints had manifested or worsened. Examples of both types of questionnaire can be found in appendices 5 and 6.

The questions asked in both questionnaires were mostly drawn from a number of existing relevant questionnaires including ENLITEN and the Buro Happold Monitoring Surveys (ENLITEN, 2013; BuroHappold Monitoring Survey, 2016). Questions about health, well-being, health status and limitations, physical activity levels and access to health care were sourced from the National Health Interview Survey 2015 (NHIS, 2015), NHS well-being survey and the 'Older people's quality of life questionnaire' (Bowling, 2012).Questions about clothing were taken from BS EN

7730.

3.4.2.2 Interviews

The interviews conducted form part of the second paper published from this project. The questions were intended to gain an understanding of people's attitudes towards heating, how they coped in the cold weather and what they thought could be done to improve their indoor environment in the cold weather.

3.5 Pilot Study

A pilot study was conducted between July and August 2016. Participants were recruited by contacting the University of the Third Age, Age UK and Transition Bath, all participants remained for the entire study. In total seven households were selected to participate in the pilot study, which represents a sample size of 17.5% of the actual study sample size. This meets Baker's (1994) recommendation that pilot studies should have a sample size of between 10% and 20% of the actual sample.

The aims of the pilot study were to:

1. Ensure the consent form and questionnaire were comprehensible.
2. Gain an understanding of suitable locations for the three sensors within people's homes.
3. Identify any gaps in the questionnaire.
4. Estimate the average time per visit.
5. Check whether participants have understood the aims and objectives of the project.
6. Check the reliability and validity of the results.

The temperature monitoring for the pilot study was successful, the iButtons recorded data as expected. The questionnaires were also answered as anticipated. It was emphasised that if the participants did not feel comfortable in answering some questions they did not have to although all were completed and a 100% return rate was achieved.

3.5.1 Pilot Study Results

The mean daily temperatures and the external temperature for the month long study are shown in Figure 3.11. The temperatures ranged from 19.2°C to 21.3°C in the living room and 17.6°C to 21.2°C in the bedroom. The largest temperature range over one house was 7.5°C in the living room and 7.9°C in the bedroom.

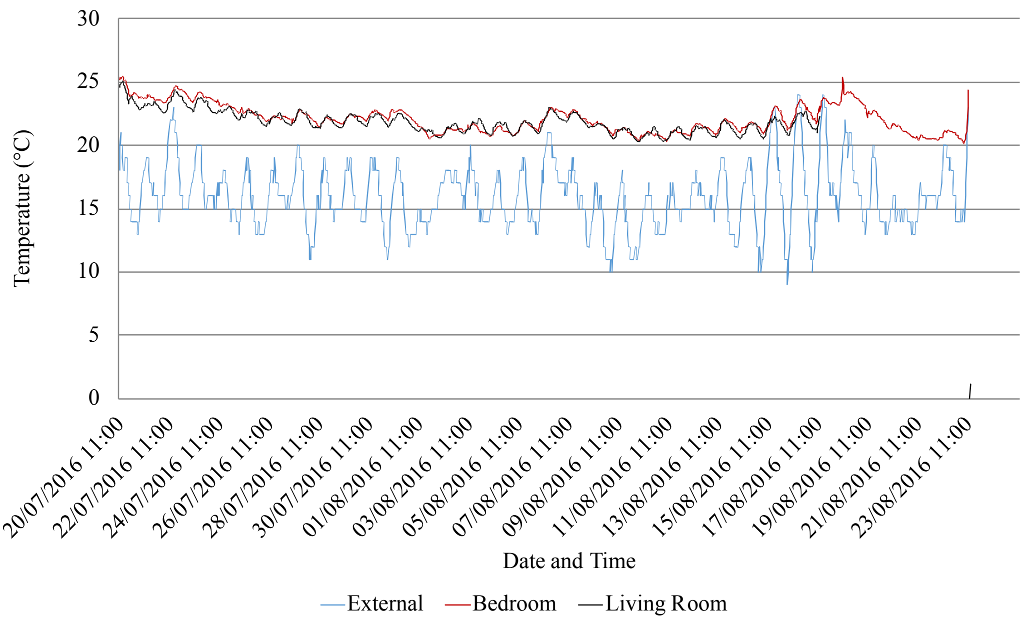

Figure 3.11: Mean internal bedroom and living room temperatures in the Pilot Study Homes and the external temperature.

Figure 3.12 shows the mean temperature of the living room and bedroom and the standard deviation. The standard deviation ranges between 0.91°C and 1.24°C, such a small standard deviation was not expected.

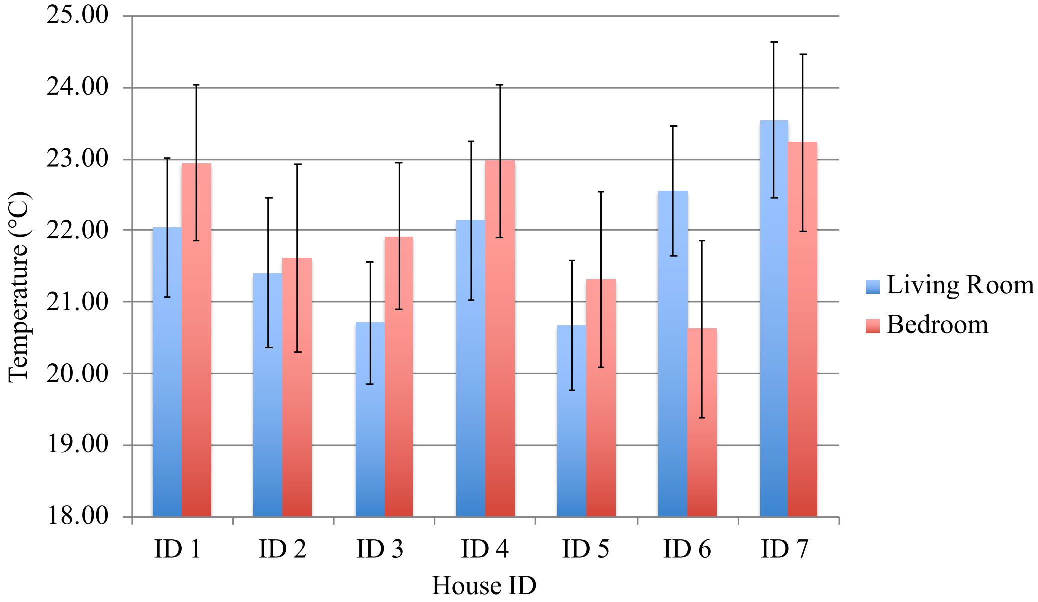

Figure 3.12: Box and Whisker plot showing mean internal temperature and standard deviation.

The pilot study results showed that measured temperatures in the participating homes were similar. The mean living room temperature was 21.9°C, which is very similar to the 21.8°C finding from the CaRB data set analysed by Beizaee (2013) and the mean bedroom temperature was 22.1°C, where the CaRB dataset was 21.6°C.

3.6 Profile of participants

There was a broad range of ages, incomes, educational attainment, house types and ages within the sample, (further breakdown in appendix 2) . There were more females than males in the project, but it does broadly reflect national conditions as the ratio in this project is 65:35 and the ratio nationally is 55:45.

3.7 Validation of sensors

During the first measurement phase (November 2016 - March 2017) additional spot measurements were taken measuring air temperature, mean radiant temperature and air velocity using the industry standard Swema Thermal Comfort equipment in accordance with ISO 7730 and ASHRAE Standard 55, as shown in Figure 3.13.

Figure 3.13: Swema Thermal Comfort Monitoring Kit.

This was in addition to measurements taken by the iButton sensors. The data collected from the Swema thermal comfort equipment and the iButton sensors have been analysed with the objective of validating the iButtons against the Swema thermal comfort measurements. As sensors such as iButtons are commonly used as a proxy for the industry standard equipment in longitudinal temperature monitoring studies it is important to understand how effective they are in comparison. Self reported metabolic rates (MET) and clothing values (CLO) were ascertained through the questionnaires, whilst air temperature, mean radiant temperature, air velocity and relative humidity were recorded by the equipment.

3.7.1 Air Temperature

The first variable to be analysed was air temperature. A correlation of the air temperature measured by the iButtons and the air temperature measured by the Swema equipment is shown in Figure 3.14. The strong positive correlation (R^2=0.86) between the air temperature measured by the iButtons and the Swema equipment suggests that iButtons are an effective proxy. On average the iButton sensors overestimated the temperature by 0.46°C, but this is expected given the accuracy of the sensors is +-0.5°C. The mean temperature recorded by the iButtons was 19.74°C and SD 2.3°C, whereas the mean temperature recorded by the Swema equipment was 19.28°C and SD 2.17°C.

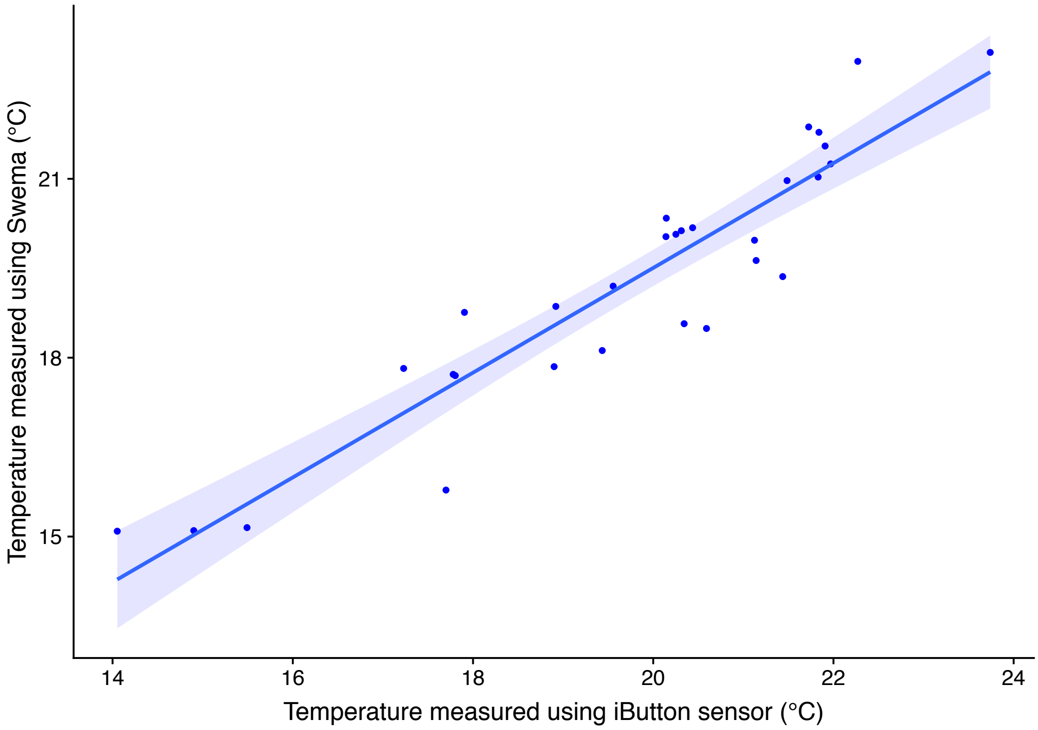

Figure 3.14: Linear regression of indoor mean living room air temperature measured using the iButtons and industry standard Swema equipment, measured in November 2016. With trend line and 95% confidence interval (shaded blue area).

This shows that iButtons are capable of measuring indoor temperatures as accurately as the industry standard equipment and are therefore suitable as a substitute where it is considered impractical to use the Swema equipment in domestic homes.

3.7.2 Relative Humidity

Figure 3.15 shows a very strong positive correlation (R^2=0.92) between the relative humidity measured by the iButtons and the Swema equipment. The average relative humidity measured by the iButtons was 57.98% with a SD of 7.85%, whereas the Swema equipment measured an average relative humidity of 58.1% and standard deviation of 6.97%. These differences are very minimal and lead to the conclusion that iButtons are a suitable alternative to industry standard monitoring kits, where cost and obtrusiveness are key considerations.

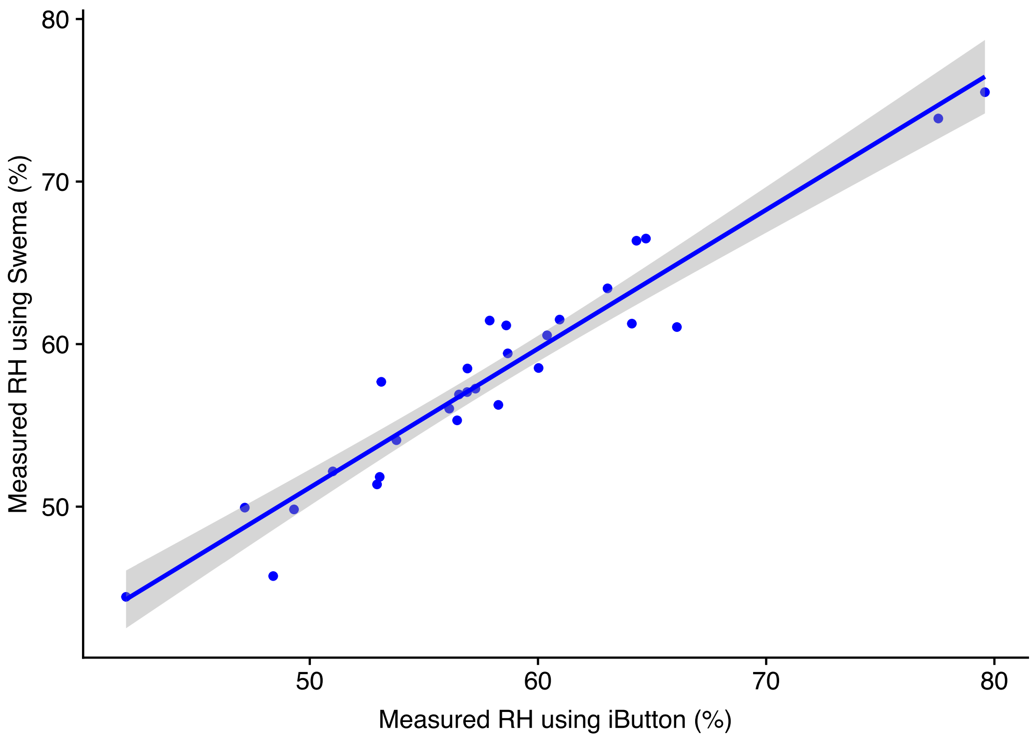

Figure 3.15: Linear regression of relative humidity measured using the iButton sensors and industry standard Swema thermal comfort equipment, measured in the 30 participating homes in November 2016. With trend line and 95% confidence interval (shaded blue area).

3.7.3 Mean Radiant Temperature

The iButton sensors are only capable of recording air temperature, not mean radiant temperature, so consequently it is common to use air temperature as a proxy for mean radiant temperature. Figure 3.16 shows the correlation between the air temperature and mean radiant temperature measured by the Swema equipment. The correlation is very strong (R^2=0.96), suggesting that is acceptable to use air temperature in place of mean radiant temperature without losing reliability in the PMV-PPD calculations.

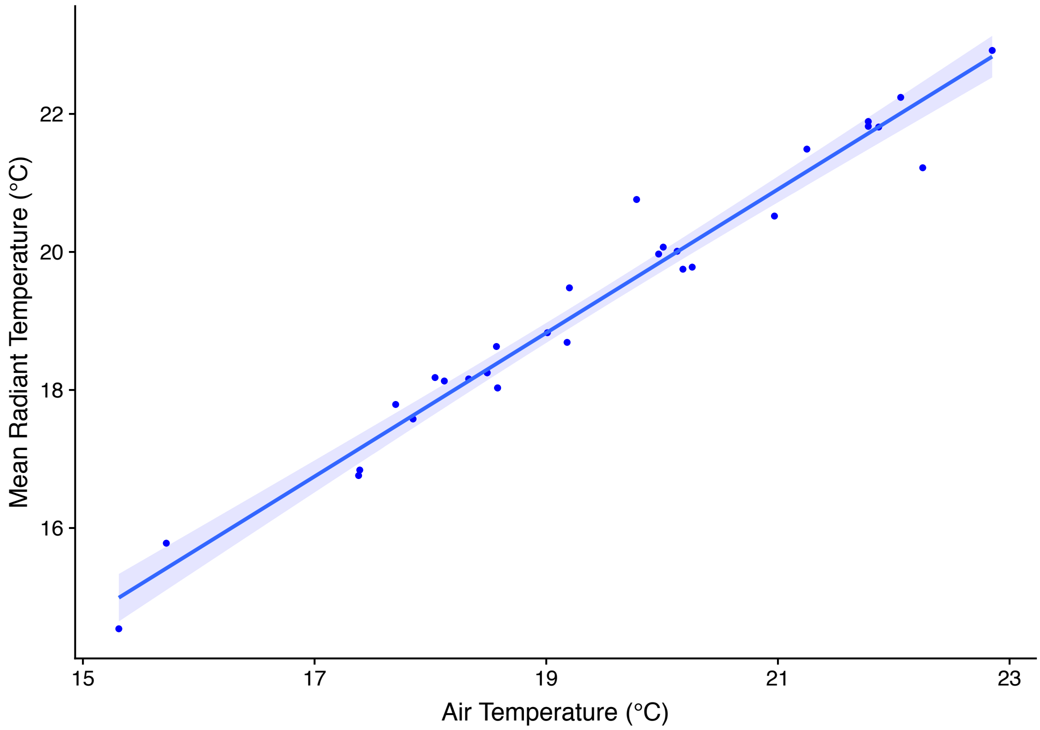

Figure 3.16: Linear regression between air temperature and mean radiant temperature, measured by the industry standard Swema thermal comfort equipment. With trend line and 95% confidence interval (blue shaded area).

3.7.4 Air Velocity

In typical PMV-PPD calculations the air velocity is assumed to be $0.1ms^{-1}$. Figure 3.17 shows that in 10% of homes (N=3), the air velocity was higher than $0.1ms^{-1}$.

As the majority of homes were below or equal to the assumed value of $0.1ms^{-1}$ it is reasonable to assume a value of $0.1ms^{-1}$ for all homes.

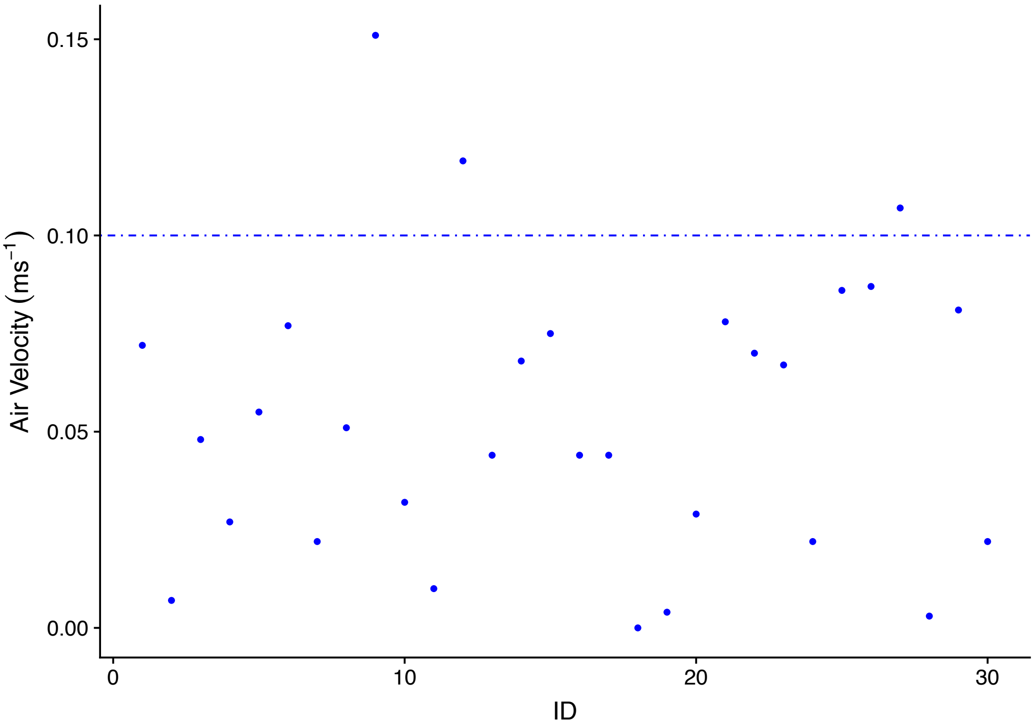

Figure 3.17: Air Velocity in each participating home (N=30) measured using the industry standard Swema equipment and the value of 0.1ms¯1 (blue dashed line) typically used as an assumed value in PMV-PPD calculations.

3.7.5 Personal Variables

The personal variables, metabolic rate and clo value, were assumed or self-reported in the questionnaire, as described below.

3.7.5.1 Metabolic Rate (MET)

Studies of a similar nature use proxy values for metabolic rate based on literature (Kane et al. 2015), which suggests a metabolic rate of $50Wm^{-2}$ (0.9met) for sedentary activities in older people compared to $58Wm^{-2}$ (1.0met) in sedentary working age populations (Parsons 2002). Hence, 0.9met has been used as representative of the metabolic rate for this study.

3.7.5.2 Clothing Value (Clo)

To obtain CLO values, self reported data from the participants was recorded in the questionnaires, which was used to calculate values based on the widely used Olesen and Dukes-Dubos (1998) 'Individual Clothing Garments: Dry Thermal Insulation Values' table. This can be found in appendix 3.

3.7.6 Impact of differences in sensor measurement for PMV and PPD calculation

The PMV and PPD values were calculated using Fanger's equations for the Swema equipment and the iButtons. Figure 3.18 shows the correlation of the PMV values, where a very strong correlation of 0.93 was observed.

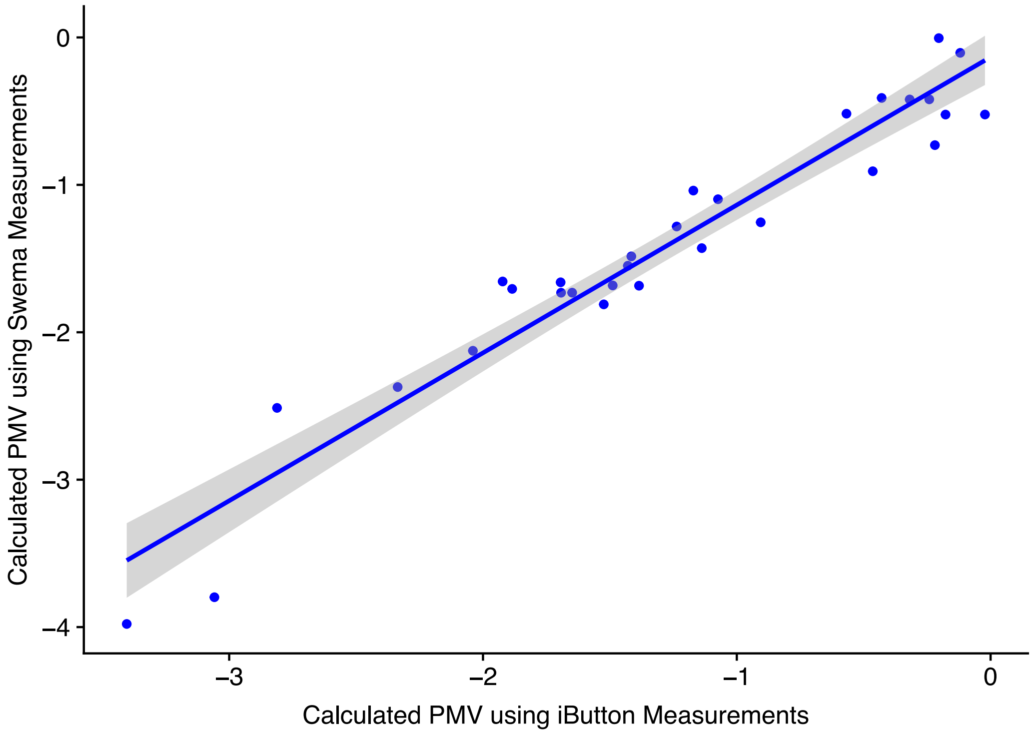

Figure 3.18: Linear regression of the PMV calculated using the measured data from iButton sensors and PMV calculated using measured data from Swema equipment. With trend line and 95% confidence interval (blue shaded area).

Figure 3.19 shows the correlation of the PPD values, where a very strong correlation of 0.95 was observed.

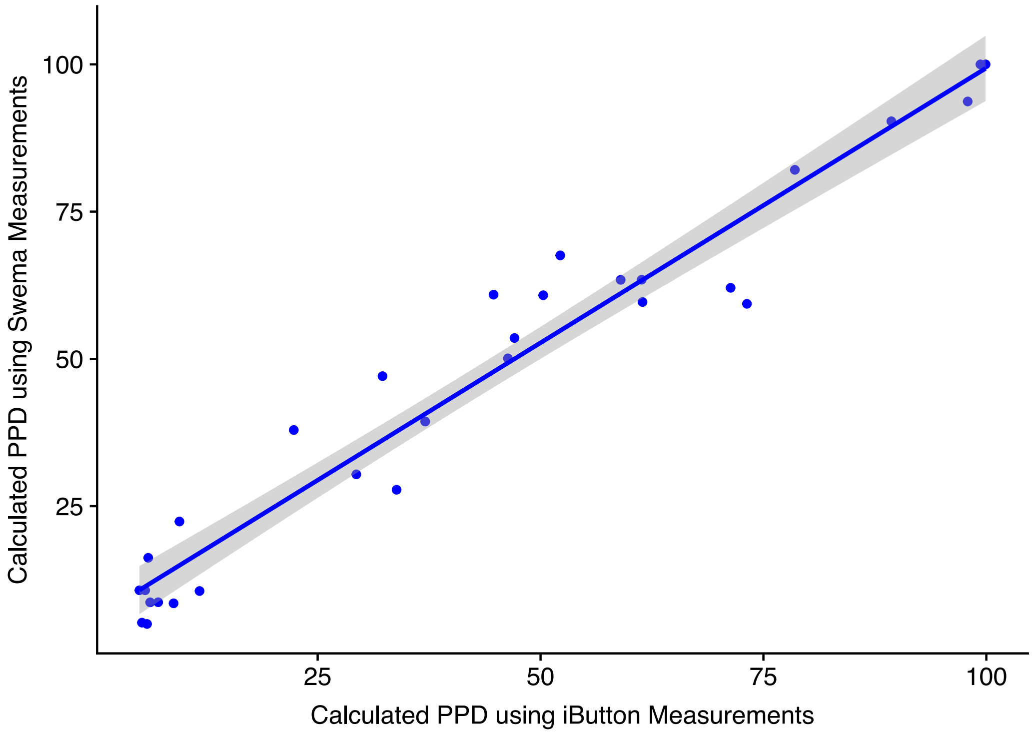

Figure 3.19: Linear regression of the PPD calculated using the measured data from iButton sensors and PMV calculated using measured data from Swema equipment. With trend line and 95% confidence interval (blue shaded area).

3.7.7 Summary

The correlations shown in the preceding figures all show very strong positive correlations. It is therefore evident that accuracy and reliability of the measured data is not compromised through use of alternative sensors, such as the iButtons, in comparison to the industry standard thermal comfort equipment. The iButton sensors are smaller, less obtrusive and cheaper than ISO standard compliant equipment. Therefore it is possible to use a practical type of sensors without compromising the accuracy of the data collected, when conducting temperature monitoring studies.

3.8 Sensitivity of PMV/PPD outputs to input variables

It is important to understand the degree to which the input variables influence the PMV and PPD output, hence a sensitivity study was conducted to enable a better understanding of the influence of air temperature, metabolic rate and clo value. For the calculations, mean radiant temperature was assumed to be the same as air temperature, relative humidity was assumed at 50% and air velocity was assumed at 0.1ms-1. PMV and PPD outputs were calculated at a range of air temperatures (16-24°C) and clo values (0.6 - 1.3 clo) for met rates of between 0.8 and 1.3, shown in Appendix 10.

For a met rate of 0.8, PMV neutral was not achieved at any of the temperature and clo combinations used. A PMV of -1 was achieved through a combination of either 21°C and 1.3 clo, 22°C and 1.1 clo, 23°C and 1.0 clo or 24°C and 0.9 clo. A PMV of -2 was achieved through a combination of either 18°C and 1.3 clo, 19°C and 1.2 clo, 20°C and 1.0 clo, 21°C and 0.9 clo, 22°C and 0.8 clo or 23°C and 0.6 clo. A PMV of -3 was achieved through either 16°C and 1.2 clo, 17°C and 1.1 clo, 18°C and 1.0 clo, 19°C and 0.8 clo, 20°C and 0.7 clo or 21°C and 0.6 clo.

Based on the above, altering air temperature by 1°C and clo by 0.1 results in a change of one point on the PMV scale. The same is true for PMV outputs using the same temperature and clo bands at met rates of 0.9 - 1.4. For this study a met rate of 0.9 was assumed (see section 3.7.5.1 for further detail), air temperature was measured and clo value self reported. Therefore, it is important to recognise the sensitivity of inputs in the context of the study. For example, when measuring air temperature only one sensor was used, and whilst the sensor was placed in accordance with BS EN 15251 (BSI 2007*a*) as far as was practicably possible, there are temperature differences of more than 1°C within most rooms. Hence, it is important to identify this as a limitation of the study, in that there could be a difference of more than 1°C between the temperature the occupant would have been experiencing and the temperature measured by the sensor, which may have some influence over the PMV result.

3.9 Overall

This chapter has introduced the research design and the methods of data collection as well as discussing the location of the study, the demographic information about the participants, the choice of sensor and how it compares to the industry standard equipment typically intended for temperature monitoring studies.

Chapter 4

Winter thermal comfort and health in the elderly

Abstract

There is said to be a strong relationship between low winter fuel consumption and increased cold-related morbidities and mortalities in the elderly. However, no study exclusively investigates the thermal conditions, energy and health in this demographic. We examine, for the first time, the validity of current thermal comfort standards and WHO minimum temperature thresholds in the 65+ demographic, through a longitudinal study of thermal conditions in homes of the elderly. We cover two typical winters using repeated monthly surveys and continuous temperature monitoring in living and bed rooms. Results demonstrate that the widely used ISO7730 PMV model significantly underpredicts comfort in this demographic. We explore the winter heating demand implications of these findings through a new PMVe model for the elderly, with a 40% lower RMSE error. Using well-calibrated thermal models, we demonstrate that PMVe predicts 44% lower winter heating demand than classical PMV. Finally, our data provides no evidence for an association between low mean monthly indoor temperature and healthcare visits for a variety of morbidities. These results question current assumptions around thermal comfort and health in the elderly, with potential implications for health and energy policy.

Keywords: Ageing Population, Thermal Comfort, Fanger, Temperature Monitoring, Health

4.1 Preamble

This chapter reports the results of two heating seasons (November 2016 – March 2017 and November 2017 – March 2018) of temperature monitoring in the 43 participating homes. All of which were located in Bath, UK and had at least one occupant aged 65 and over. This represents the fist UK based longitudinal temperature monitoring study to focus on winter temperatures found in homes occupied by older people. This chapter specifically addresses Research Question 1 'During winter periods what internal temperatures are achieved in participating homes, how comfortable are the participants and how effective is Fanger's Predicted Mean Vote (PMV)/ Percentage People Dissatisfied (PPD) model in predicting thermal comfort of homes occupied by over 65 year olds?'

Before the study commenced, ethical approval was obtained from the research ethics committee of the Department of Architecture and Civil Engineering at the University of Bath. All participants signed a consent form at the beginning of the first phase (November 2016), where they were informed that their data would be confidential and stored in accordance with the Data Act 1998. Furthermore, they were assured that they did not have to answer anything they did not feel comfortable answering and they could withdraw from the study at any point.

4.2 Declaration of Authorship

<table>
<tr><td colspan="10">This declaration concerns the article entitled:</td></tr>
<tr><td colspan="10">Winter thermal comfort and health in the elderly.</td></tr>
<tr><td colspan="10">Publication status (tick one)</td></tr>
<tr><td>Draft manuscript</td><td></td><td>Submitted</td><td></td><td>In review</td><td>✓</td><td>Accepted</td><td></td><td>Published</td><td></td></tr>
<tr><td>Publication details (reference)</td><td colspan="9">In review in Energy Policy Journal</td></tr>
<tr><td>Candidate's contribution to the paper (detailed, and also given as a percentage).</td><td colspan="9">The author of this thesis has primarily contributed to defining the methodology, conducting the data collection and writing the manuscript. The proposed PMVe model was entirely developed by M. Herrera and validation of the proposed model was entirely conducted by C. Liu and W. Chung. Each authors exact contributions are as follows:

C Hughes: Formulation of Ideas (80%); Design of Methodology (80%); Data Collection (100%); Data Analysis (80%); Preparation of Manuscript (80%)

S. Natarajan: Formulation of Ideas (20%); Design of Methodology (20%); Data Analysis (20%); Preparation of Manuscript (20%)

M. Herrera: Design of PMVe Model (100%)

C. Liu and W. Chung: Validation of PMVe Model (100%)</td></tr>
<tr><td>Statement from candidate</td><td colspan="9">This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.</td></tr>
<tr><td>Signed</td><td colspan="5"></td><td colspan="2">Date</td><td colspan="2"></td></tr>
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4.3 Introduction

A baby born post-millennium in the UK is likely to reach their 100th birthday. This represents a remarkable increase in mean life expectancy of 30 years since the 1950s, slightly higher than the mean global increase of 23 years (Riley 2005). Ageing populations, particularly in the "very old" demographic, are globally recognised as an important issue, increasing pressure on health services, social care, housing and the economy (Christensen et al. 2009, Wouters 2017).

By 2050, 25% of the UK population is expected be aged 65+, compared to 18% in 2018 (ONS 2017*b*), with the greatest population increases being seen in the octogenarian and older categories (Wouters 2017). A demographic shift in this way will have implications for climate change, energy supply, housing and health. For example, a key platform for the UK's energy policy in support of those aged 65+ is the Winter Fuel Payment (≈ £300). However, though all those over 65 are automatically eligible, only 24% are in fuel poverty (Boardman 2010).

The UK housing stock is notoriously energy inefficient and despite a relatively mild climate, excess winter mortality figures are higher than in other countries with similar or colder climates (Rudge and Gilchrist 2005). This is despite significant Government investment in improving the energy performance of homes (G.Hamilton et al. 2014), which has resulted in a reduction, but not elimination, of cold homes (Anderson et al. 2014), with the rising cost of fuel and occupant behaviour also implicated in instances of cold homes and EWDs (Zainol et al. 2017, Gram-Hanssen 2014).

Similar studies focus on low income households (Kane et al. 2015, Oreszczyn 2006), but there is no clear link between cold homes and deprivation (Hajat et al. 2007). In fact, the most adversely affected homes tend to be large owner-occupied houses that are difficult to heat (Wookey et al. 2014). It is estimated that over a third of such housing is owned and occupied by older people (Hamza and Gilroy 2011).

Furthermore, it is common for older people to spend large amounts of time in their home. For example, 65 year olds are said to spend over 85% of their time at home, rising to over 95% at 85 years and above (Hamza and Gilroy 2011). Long durations spent indoors result from declining health, financial economy and loss of companions that would have provided company for activities outside the home. In addition, older people tend to lead more sedentary lifestyles (Wookey et al. 2014), which generally necessitates a higher internal temperature. It is therefore widely assumed that the homes of the elderly require more energy due to higher internal temperatures and longer heating periods (Roberts 2008*b*, Devine-Wright et al. 2014).

However, there is insufficient evidence to support this assumption. For example, the elderly may often have to make severe compromises to achieve satisfactory internal temperatures; and in extreme cases be forced to decide between food and heating, with many prioritising heating (O'Neill et al. 2006*a*). More commonly however, older people manage by not heating bedrooms, bathrooms and living rooms in order to save money (Hamza and Gilroy 2011). Most older people are retired and living on pensions which are lower than incomes of working age populations. Given that older people spend large amounts of time in their homes and therefore require longer heating periods, it is unsurprising that many struggle to afford enough fuel to achieve comfortable temperatures that maintain their health. This is borne out in the worrying but unsurprising statistic that about 28% of those in fuel poverty are aged 65 and over (BEIS 2018*a*).

These are alarming findings when considering the health problems associated with cold homes, which are harmful at any age, but can be fatal for older people. A growing body of evidence is making the link between quality housing and good health increasingly apparent (Liddell and Morris 2010, Hood 2005). A particular emphasis is also being placed on the strong association between sub-optimally heated homes and the detrimental health impacts that arise from this (Healy and Clinch 2004). These include the onset of cardio and cerebrovascular problems including strokes, pulmonary embolisms and myocardial infarctions (Crawford et al. 2003), the suppression of the immune system, the exacerbation of respiratory conditions and rheumatism and arthritis (Healy and Clinch 2004). Most strikingly, there appears to be a link between cold homes and excess winter deaths (EWDs) (Shortt and Rugkasa 2007). There are around 28,600 EWDs in the UK each year, 92% of which are attributed to those aged over 65 (Wookey et al. 2014). This translates to an EWD rate of 0.2% in the over 65 demographic ONS (2018*c*). Following a period of cold weather, EWDs continue to occur for up to 4 weeks, with the peak number of older people admitted to Accident and Emergency with respiratory conditions occurring in December and January (Elliot et al. 2008). In addition, GP visits increase dramatically during cold weather. For every degree that the external temperature decreases below 5°C there can be as much as a 19% increase in the number of consultations held with older people suffering respiratory problems (Hajat et al. 2007). Older people are most at risk of the health impacts of cold homes because the ageing process results in the body being less able to maintain and regulate its core temperature, due to a lower metabolic rate and a slower vasoconstriction rate (Day and Hitchings 2011). This is often further complicated by the fact that older people are less capable of recognising temperature changes and consequently less likely to make necessary changes to their environment to protect their health (Wookey et al. 2014).

Overall, it is clear that there is a strong association between morbidity and mortality in the elderly due to the indoor environmental conditions in their home. At the same time, little is known about the precise nature of these conditions – especially thermal conditions – and whether these conditions emerge due to, or the lack of, choice. Investigating this requires data on not just the indoor thermal conditions but also whether the elderly find them comfortable. This paper sets out to address this gap.

We first briefly introduce the assessment of thermal comfort using the PMV standard, followed by a discussion of current recommended internal temperature guidelines and evidence from other field studies, in Section 4.4. Section 4.5 describes our methods for the field study underpinning the data in this paper. Section 4.6 discusses the results of our field study compared against current standards, for both thermal comfort and health. Section 4.7 derives an age-corrected model for use with the elderly, based on our findings, and then tests the implications of using the new model on winter heating energy demand. Finally, Section 4.8 sets our results in context of the current state of the art and points to future work.

4.4 Current standards for thermal comfort and health

'Thermal Comfort' is the term used to describe a balance of environmental and personal factors that lead to a person feeling satisfied and comfortable in their thermal environment (Nicol and Roaf 2017). Two key approaches for assessing thermal comfort are the so-called 'fixed' (Fanger 1970) and 'adaptive' models (de Dear and Brager 1998). Of these, the latter can only be used in naturally ventilated buildings that are neither mechanically heated nor cooled. Since we are reporting on a winter field study in centrally heated homes, we consider only the 'fixed' model developed by Fanger, below.

4.4.1 Fanger's Thermal Comfort Model

Fanger's PMV-PPD model is the most widely used means of analysing thermal comfort. It uses two key metrics: the Predicted Mean Vote (PMV) and the Percentage of People Dissatisfied (PPD), to describe the likely thermal comfort of a large group of people in a given location. This model was created through research in climate chambers, primarily with around 1,300 college students, followed smaller experiments with about 130 elderly subjects.

Methods to calculate PMV and PPD are described in ISO 7730 (BSI 2005) and ASHRAE Standard 55 (ASHRAE 2013). Essentially, they require the measurement (or prediction) of six factors known to influence thermal comfort including four environmental variables: air temperature, radiant temperature, air velocity and humidity; and two personal variables: clothing (Clo Value) and metabolic rate (levels of activity). These are converted into acceptability categories (i.e. the building type and associated activities) in the standards: ISO 15251 (BSI 2007*a*) specifies four categories including one for the elderly whilst ASHRAE 55 specifies a general category with modifications (e.g. for elevated air speeds), but no specific guidance for use with the elderly (Table 4.1).

Table 4.1: Application of current thermal comfort standards to the elderly.

Category	**PPD (%)**	**PMV**	t_o **(°C)** ‡	**Explanation**
I	< 6	$-0.2 < \text{PMV} < +0.2$	23 ± 1	High level of expectation; recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and **elderly persons**.
II⋆	< 10	$-0.5 < \text{PMV} < +0.5$	23 ± 2	Normal level of expectation and should be used for new buildings and renovations. **Applies to the elderly** as ASHRAE 55 does not provide a separate classification.
III	< 15	$-0.7 < \text{PMV} < +0.7$	23 ± 2.5	An acceptable, moderate level of expectation and may be used for existing buildings.
IV	> 15	$\text{PMV} < -0.7$ or $+0.7 < \text{PMV}$		Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.

4.4.2 Recommended minimum indoor temperatures

Whilst the thermal comfort criteria above are designed to produce "comfortable" environments, minimum indoor temperature recommendations have been produced with the primary aim of ensuring occupant health. It is widely accepted that there are clear links between extremes of internal temperatures and harm to health. Estimates predict that around 30% of EWDs are a direct result of cold homes (Rudge 2011) with research showing that the risk of cold related mortality during the winter period increases by 20% for the coldest 25% of homes (Wilkinson et al. 2001).

As a consequence of these concerns, the World Health Organisation (WHO) produced some of the earliest guidance on acceptable internal temperatures, particularly with a view to protecting the elderly: 18°C for all rooms, but 20–21°C if occupied by the elderly (WHO 1987). These recommendations have been used internationally, including the basis for recommendations made by the UK Government until 2014 (Wookey et al. 2014) and Age UK (AgeUK 2018*b*), albeit with the modification that 18°C be used for all rooms, and 20–21°C for the living room. Given that the WHO guidance is more than 3 decades old, and the studies informing these thresholds older still, there have been suggestions that a reassessment may now be necessary. A key dispute is on whether these recommendations are (Ormandy and Ezratty 2012), or not (Wookey et al. 2014), supported by clear evidence. A systematic review on minimum indoor temperature thresholds by Public Health England (Wookey et al. 2014), concluded that there was inadequate evidence to support a 21°C limit for living rooms and suggested a return to the minimum of 18°C as originally proposed by the WHO for all rooms. It is noteworthy that this review specifically highlights lack of adequate data on health impacts on specific groups including the elderly.

4.4.3 Field Studies

Field studies are necessary to obtain evidence on actual and preferred indoor temperatures. To date there have been a small number of UK temperature monitoring studies, of varying sample sizes, as summarised in Table 4.2. Of these, only two studies focused exclusively on the older population, but were conducted in the 1970s before the widespread uptake of central heating systems and are therefore likely to be outdated. For studies conducted since the 1990s, when central heating had already seen widespread uptake, the mean living room temperature was 19.1°C ($n = 10, s = 0.6$°C) and 17.3°C ($n = 6, s = 1.0$°C) for bedrooms. This suggests that the British stock, as a whole, is only partially meeting the original WHO recommendations of a minimum 18°C temperature throughout the house (since bedrooms are lower than this on average), and is not meeting the recent UK guidance on living rooms at 21°C and bedrooms at 18°C. It also seems likely, though there is little hard evidence due to lack of demographic segmentation in these studies, that homes of the elderly are not achieving the elevated WHO standard of 20–21°C.

What is less clear, however, is whether people are happy at these lower temperatures, or whether they desire warmer temperatures but are unable to achieve them. Hence, this requires further investigation – particularly in the elderly.

Table 4.2: Chronological summary of domestic temperature monitoring studies in the UK.

Study	Period	Sample size	Coverage	Sensor Type	f	$\bar{t}_{LR}$ (°C)*	$\bar{t}_{BR}$ (°C)*	SES
Fox (Fox et al. 1973)	1973	1,020	GB		⊙	16.2		No
Collins (Collins et al. 1977)	Jan - March '72 Jan - March '76	47	London		⊙	18.4		Partial
NFST (Hunt and Gidman 1978)	Dec '77, Jan - March '78	901	UK		⊙	18.3	14.6	Partial
Nevrala (Nevrala and Pimbert 1981)	Sep '77–May '78	40	London, NE England		60	20.6	16.5$^{\diamond}$	Yes
EHCS (DOE 1995)	1991	4,788	UK		⊙	18.7	16.7†	Partial
Oseland (Oseland 1994)	1991–92	515	UK		⊙	19.2		No
EHS-EHCS (DOE 1996)	1996	17,511	UK		⊙	19.5	18.1†	Partial
Warm Front (Oreszczyn 2006)	2001–2, 2002–3	1,604	Birmingham, Liverpool, Manchester, Newcastle, Southampton	Gemini TinyTag	30	19.1	17.1	Partial
Yohanis (Yohanis and Mondol 2010)	Feb '04 - Jan '05	25	N Ireland	Gemini TinyTag	30•	19.7	18.6	No
CaRB HES (Huebner et al. 2013) (Kelly et al. 2013)	Nov '07–Jan '08 (LR) Jul '07–Feb '08 (BR)	248	England	HOBO UA001-08	45	19.0		No
4m (Kane et al. 2015)	2009–10	249	Leicester	HOBO UA001-08	60	18.5	17.4	Partial
CALEBRE (Vadodaria et al. 2014) ‡	Feb - May 2010	20	Loughborough	HOBO UA001-08	60	18.7	17.2	Yes
EFUS (Huebner et al. 2018)	Feb '11, Dec '11, Jan '12	635	England	Gemini TinyTag	20	18.25	18.15	Partial
REFIT (Kane et al. 2017)	2014	20	Loughborough	HOBO UA-001-64 and HOBO U12-012	30	19.8		Yes
ARBED (Poortinga et al. 2018)	Jan – March '14 Nov - April '15	99	Wales	TinyTag Ultra 2	15	18.53	18.16	No

Notes:

f is sampling frequency in minutes

⊙ represents "spot measurements"

* LR is living room and BR is bedroom

$\bar{t}$ is mean temperature

† coded varyingly as 'hall / passage / other'

$^{\diamond}$ when $\bar{t}$ external = -1 °C

SES whether a thermal comfort or other socio-economic survey was undertaken

‡ focuses on solid wall homes only

• measurement taken every second and averaged over 30 minute period.

4.4.4 Research Questions

The preceding review suggests that there is inadequate evidence on the effect of the indoor thermal environment on the elderly. Little is known about what temperatures are achieved, especially in winter when EWDs are disproportionately weighted towards the elderly. Even less is known about whether these temperatures are a result of choice or the lack of it, and what effect these may be having on their health. This is especially concerning given that this demographic is most at risk, and increasing in proportion with respect to other age classes in the population. Consequently, this paper addresses three key questions:

1. Do the temperatures achieved in the homes of the elderly meet the WHO and PMV standards?
2. Are the temperatures achieved in the homes of the elderly deemed to be comfortable by the occupants?
3. Are the achieved temperatures associated with increased or decreased health problems?

4.5 Methodology

This section describes the longitudinal temperature monitoring study designed to address the above research questions. The study was conducted in the city of Bath, South-West UK. Nationally, the number of pre-1919 buildings represents 21.5% of the total stock, but this rises to 30% in Bath (Moran et al. 2012). Buildings of this age often pose complex challenges in light of the increasing emphasis on emissions reductions. These houses are usually single-glazed solid walled dwellings with legally protected status which often precludes any modernisation. Consequently, they are inefficient and hence are likely to be poorly heated, making Bath an ideal location for the study. A secondary effect of studying such homes is the possibility of participants suffering fuel poverty, which the UK government aims to mitigate by 2030. Whilst this study did not set out to exclusively study those in fuel poverty, we consider these implications in Section 4.8.

4.5.1 Participant selection

Bodily changes that result in a diminished ability to respond to temperature changes, exacerbating common health conditions, are said to commence around 65 years (Hajat et al. 2007). Hence, the main requirement was for participant age to equal or exceed 65 years. Exclusion criteria were designed to exclude those unable to give informed consent to participate in the study, or those whose lifestyle or behaviour is not representative of routine practice (based on Win et al. (2015)). This included: (i) severe mental retardation or illness (ii) stroke or injury resulting in loss of speech and (iii) those who were bedridden or wheelchair bound.

A key question for longitudinal studies of this type is sampling frequency. An important consideration was participant recall since the aim was also to observe changes in health metrics over the sampling interval (such as number of GP visits, onset of temperature-related illness); so sampling frequency had to account for participants' ability to remember what had occurred over each sampling interval. Clearly, the more frequent the sampling, the better the recall, but also the greater the risk of participant fatigue. An initial pilot involving 7 participants over 5 weeks suggested that fortnightly frequency was feasible but most participants were able to recall events over a four-week period.

A 1-page letter was created inviting participation in the project, with the only limitation being resident age. The letter informed potential participants (i) of the aims of the study, (ii) that temperature sensors would be placed in their home between November 2016 and September 2018, (iii) that they would be asked to answer thermal comfort and health questionnaires on a monthly basis, and (iv) that they would have the right to withdraw from the study at any time.

Two methods of recruiting participants for the study were used:

- *Random sampling*: In order to minimise bias in the sample, a random sampling process was adopted. Twelve areas of Bath were selected, with two or three streets in each area targeted for the letters to be posted. Six hundred letters were posted in total through this process. Households expressing interest were either emailed further information (another 1 page letter detailing more information about timescales and project phases) or phone called, depending on their preference.
- *Targeted sampling*: To increase the likelihood of reaching an older demographic, presentations were undertaken to groups such as Age UK, University of the Third Age, Lunch Clubs and St. John's Care, in Bath. Each presentation lasted 30 minutes, followed by another 30 minutes of Q&A, with the chance to ask questions individually. Interested members of the audience were provided a letter incorporating the briefing letter and the further information letter as in the random sampling.

The random sampling process generated 25 participating homes (4.2% response rate), and the targeted sampling a further 18, bringing the study total to 43 participating homes with a total of 59 occupants. Each home designated one person to respond to the surveys to ensure continuity. All participants live within a three mile radius of Bath. The mean age of our sample is 76.3 years (n = 59, s = 9.1 years).

A demographic breakdown of all participants in Table 1 suggests that there is a diversity of age-class, annual incomes, house types and house ages, with little systematic bias. Although female:male ratio is 65:35, this is reasonably consistent with

ONS data on the 65+ demographic where nationally the ratio of female:male is 55:45 (Census 2011).

Table 4.3: Demographic and House Characteristics

Demographic Characteristic		Number of Participants
Age	65-69	15
	70-79	16
	80-89	9
	90+	3
Number of Occupants	1	28
	2	12
	3	3
	4+	0
Income (£)	6,000	1
	6-13,000	11
	13-19,000	9
	19-26,000	8
	26-32,000	2
	32-48,000	5
	48-64,000	1
	65,000+	1
	Prefer not to say	5
Tenure	Owner Occupied	36
	Private Rented	4
	Social Rented	3

House Type	Detached	10
	Semi-Detached	16
	Terrace	8
	Flat	8
	Bungalow	1
House Age	Pre-1919	15
	1920-44	4
	1945-64	11
	1965-84	6
	1985+	7
Wall Type	Cavity	28
	Solid	15
Insulation	Yes	19
	No	24
double Glazing	Yes	33
	No	10

4.5.2 Sensors

The typical household spends the majority of occupied hours in the living room and bedroom (90% over a 24-hour period)(Hoppe and Martinac 1998). Hence, these two rooms are the chosen sensor locations for this study. This choice, in common with other studies of this type (Kane et al. 2015, Huebner, McMichael, Shipworth,

Shipworth, Durand-Daubin and Summerfield 2013*a*), balances the need for representative data against the cost of sensing. Since the aim was to measure internal temperatures, it was also important to determine to what extent the measured temperatures were a result of the operation of the home's heating system. A good proxy for this is the temperature of a typical radiator that is known to be operated throughout the heating season. Hence, a total of three sensors were placed in each home:

- living room sensor
- bedroom sensor
- radiator sensor

Relative humidity can have an impact on not only thermal comfort but also health. For example, high relative humidity encourages mould growth in the presence of low temperatures, which can exacerbate respiratory problems. Hence, this study recorded relative humidity co-incidentally with temperature. However, sensors which measured both air temperature and relative humidity were markedly more expensive than sensors which solely measure air temperature. To balance costs against measuring sufficient data, one relative humidity sensor per home was judged to provide a starting insight into any emergent problems. Consequently, the living room sensor measures both air temperature and relative humidity, while the bedroom measures solely air temperature.

4.5.2.1 Sensor selection

For the measurement of air temperatures in the living and bedrooms, prior work in this area has suggested a minimum accuracy of 0.5°C or better (Martin and Watson 2006, Huebner, McMichael, Shipworth, Shipworth, Durand-Daubin and Summerfield 2013*b*, Yohanis and Mondol 2010). Maxim's iButton range (e.g. the DS1922L-F5) or the HOBO UA-001-08 temperature sensors meet these requirements and are hence the most common choices for similar studies in the literature. Table 4.4 shows the key differences between these two sensors.

Table 4.4: Comparison of the iButton DS1922L-F5 and HOBO UA-001-08 temperature sensors.

Sensor	Dimensions	Accuracy	Range	Measurement interval	Reading limit	Comments
 iButton DS1922L-F5	16mm (D) x 5mm (H)	± 0.5°C	−40°C to +85°C	1s to 273h	4096	Sensors are small, resistant to dirt and moisture. Can easily be mounted on a variety of surfaces.
 HOBO UA-001-08	33mm (L) x 32mm (W) x 58mm (H)	± 0.53°C	−20°C to +70°C	1s to 18h	6500	Larger and pendant shaped, hence more difficult to mount on surfaces, more obtrusive than iButton.

Legend: (D)iameter, (L)ength, (W)idth, (H)eight, (s)econds, (h)hours

Both sensors were exposed to the likely range of real world temperatures through an initial test conducted in a climate chamber, comparing HOBO UA-001-08 sensors with iButton DS1922L-F5 sensors. The climate chamber was set to span a temperature range of 30°C at 30 minute intervals, between 5°C and 35°C, with relative humidity set at a constant 50%. The sensors were programmed to record every 10 seconds. The only sensor to span the full 30°C were the iButtons; the HOBO sensors measured a range of 25°C. As the iButton results suggested a more reliable reading they were chosen for the project.

4.5.2.2 Sensor Installation in Homes

Living room and bedroom sensors were located away from windows and local sources of heat, approximately 1.5 metres above the ground (e.g. on a shelf), in accordance with ASHRAE 55 Class I. Although further measuring using the Swema ISO compliant monitoring equipment meets the Class II requirements (de Dear and Brager 1997). Radiator sensors were embedded in 5cm of 9mm wide pipe insulation and taped to the inlet pipe, as shown in Figure 4.1.

Figure 4.1: Preparation and placement of radiator sensor

Although other studies have chosen a sampling frequency of 60 minutes or lower, our sensors were set to record spot measurements every 90 minutes (i.e. 16 readings/day); due to the total memory capacity of the sensors. This is unlikely to affect results as homes – especially those of the elderly – tend to adopt stable heating patterns that are longer than 90 minutes.

4.5.3 Other variables required to compute PMV/PPD

The calculation of PMV and PPD requires data on four environmental and two personal variables. The environmental variables are: (**i**) air temperature (t_a), (**ii**) relative humidity (RH), (**iii**) mean radiant temperature (t_{rm}) and (**iv**) air velocity (V_a). Of these, t_a (living and bedroom) and RH (living room) were part of the longitudinal monitoring, the latter being taken as representative of the house as whole. Data for the remaining variables were computed as follows.

4.5.3.1 Mean radiant temperature (t_{rm}) and air velocity (V_a)

Several studies have shown that differences between radiant and air temperatures in typical indoor environments are usually small (Walikewitz et al. 2015). We assessed this through a transverse survey in November 2016 using the ISO 7730 compliant Swema equipment, covering the 30 homes that had joined our study by that date. A regression of t_a and t_{rm} shows a strong correlation ($R^2 = 0.96$), suggesting that t_a is a good proxy for t_{rm} (Figure 4.2). Measurements of air velocity taken at the same time indicate that all but three homes had $V_a < 0.1 ms^{-1}$ (Figure 4.3). Hence, our calculations assume 0.1 ms^{-1} throughout.

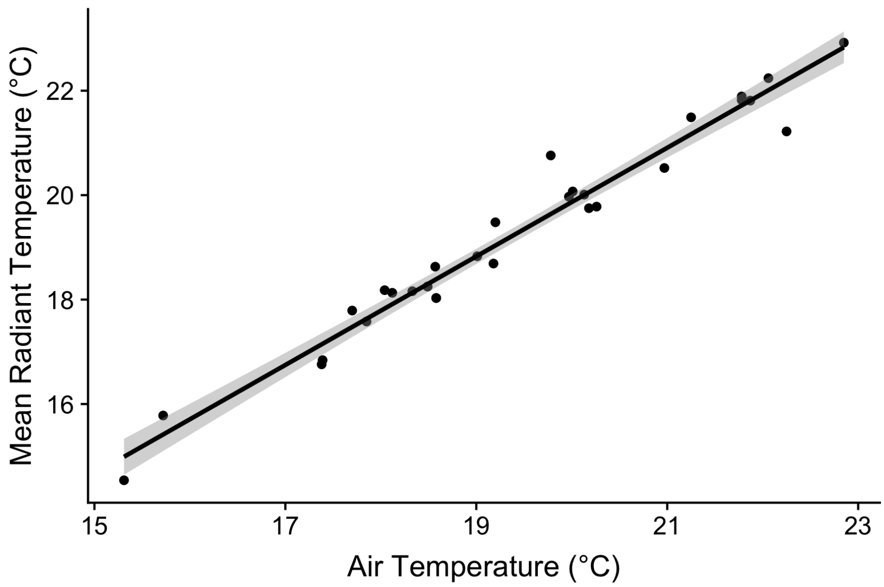

Figure 4.2: Scatter plot of mean radiant (t_{rm}) and air (t_a) temperatures

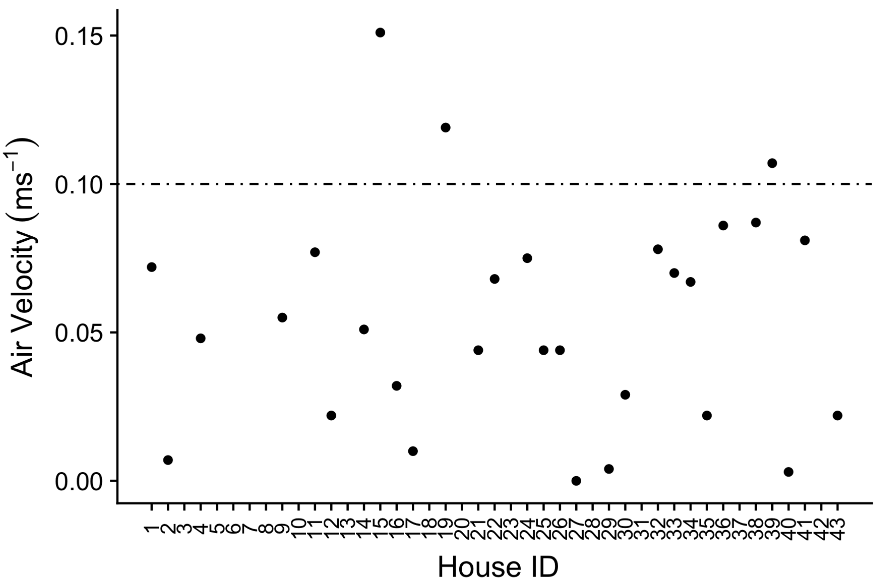

Figure 4.3: Air velocity (V_a) against the default air velocity of $0.1ms^-1$ used in ISO 7730. .

4.5.3.2 Personal Variables

The two personal variables required to compute PMV and PPD are: (**i**) clothing insulation (clo) and (**ii**) metabolic rate (met) which were obtained through survey data and literature. The former was computed using the widely used clothing ensemble conversions available in Olesen and Dukes-Dubos (1998) (Parsons 2002). Figure 4.4 shows the range of clothing ensembles for each participant.

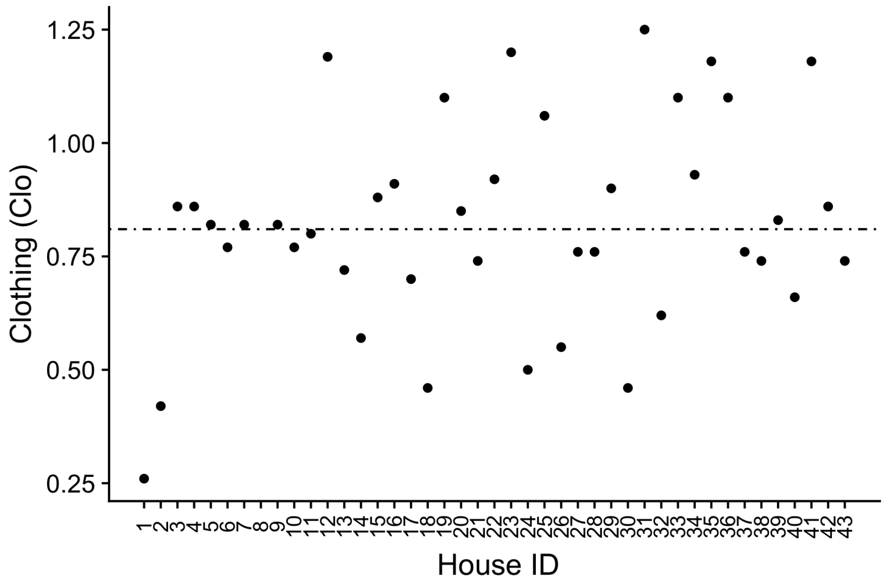

Figure 4.4: Clothing ensembles worn by participants with the average clo value of 0.81 (blue dashed line)

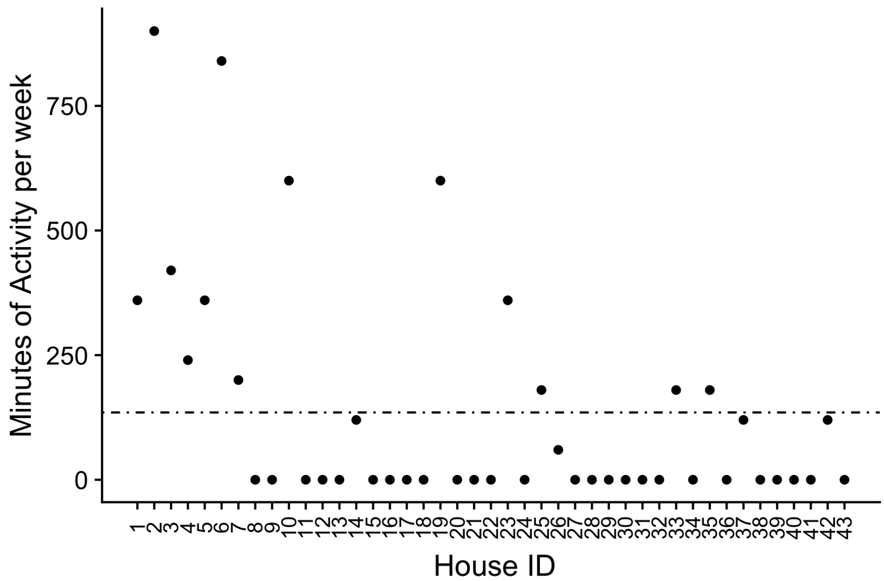

Figure 4.5: Weekly activity levels of participants with the average number of minutes spent exercising (blue dashed line)

Metabolic rates in older people are known to be lower than working age adults, but are difficult to obtain without significant personal obtrusion and cost. Studies of a similar nature use proxy values based on literature (Kane et al. 2015), suggesting a metabolic rate of 50Wm^{-2} (0.9met) for sedentary activities in older people compared to 58Wm^{-2} (1.0met) in sedentary working age populations (Parsons 2002). Since only 40% of our sample conducts regular exercise (Figure 4.5) and a majority (85%) of occupied hours fall into the sedentary category (i.e. <150 minutes activity per week (WHO 2018, NHS 2018)), we take 0.9met as representative of the metabolic rate for our participants.

4.5.4 Surveys

The survey had the following key features:

- The survey was designed to assess both thermal comfort and health. The thermal comfort survey was based on a reduced set of the standard survey design contained in ASHRAE 55 and commonly used in other studies (Critchley et al. 2007, BSI 2007*a*, ASHRAE 2013). Health metrics were adopted from the NHS Health Survey for England (Service 2016), the Short Form-36 Questionnaire (RAND 1980) and the 'Older People's Quality of Life Questionnaire' (Bowling 2013).
- We initially expected to undertake paper-based surveys for a population that is often seen as technologically ill-at-ease. However, initial interviews suggested that the majority (85%) of our participants were not only technologically savvy but preferred this as the means of communication with the researchers. Hence, the survey was administered electronically for all but 6 participants. An added benefit of this approach is that each survey is automatically timestamped allowing us to build a picture of thermal comfort at the time the survey was

submitted using our sensor data.

- Although initial surveys were returned at a fortnightly frequency, the response rate settled to a monthly frequency. The overall return rate was high at 65% per month, providing confidence in results.

4.6 Results

Median internal living room and bedroom temperatures for each home across the two winters (2016-17, 2017-18) are shown in Figure 4.6. Data for rooms are filtered against typical occupancy: living rooms between [0700, 2100) and bedrooms between [2100, 0700). For the first winter (2016-17) the mean internal living room temperature was 18.9°C (s = 2.27°C) and the mean internal bedroom temperature was 18.17°C (s = 2.54°C) and for the second winter (2017-18) the mean internal living room temperature was 18.7°C (s = 2.5°C) and the mean internal bedroom temperature was 17.6°C (s = 2.96°C). A Pearson's Product Moment Correlation Coefficient of the two winters shows a strong positive correlation suggesting that the internal temperatures did not differ significantly between the two winters ($R^2 = 0.79$ for living rooms and $R^2 = 0.87$ for bedrooms).

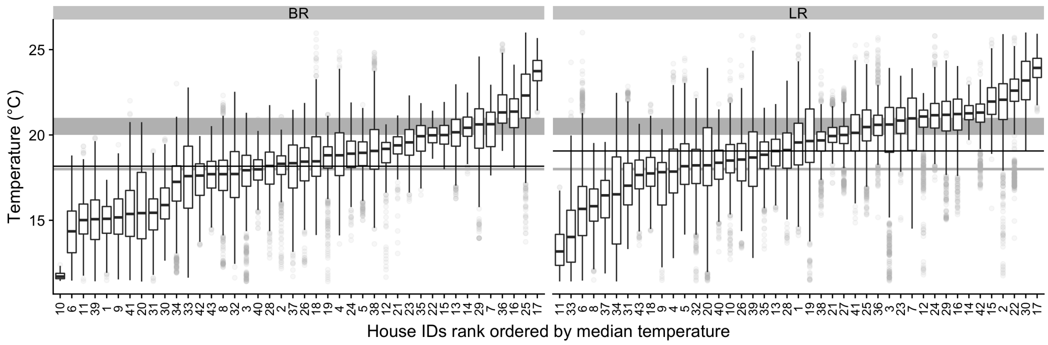

Figure 4.6: Ranked median internal bedroom (BR) and living room (LR) temperatures for each house across the winters of 2016-17 and 2017-18. Living rooms evaluated between [0700, 2100) and bedrooms between [2100, 0700). The grey band shows the WHO suggested minimum threshold internal temperatures for the elderly (20-21°C), and the grey line shows the minimum recommendation for all homes (18°C). The black lines show means for each room.

Figure 4.7 shows that the most common heating pattern was for the heating to be turned on twice per day, supporting our hypothesis of stable heating patterns. Homes 34 and 39 do not use central heating and are hence colder than the cohort average, though mean living room temperature in ID39 is above the 18°C threshold. The radiator sensor for ID27 shows 0 events due to poor contact with the radiator surface.

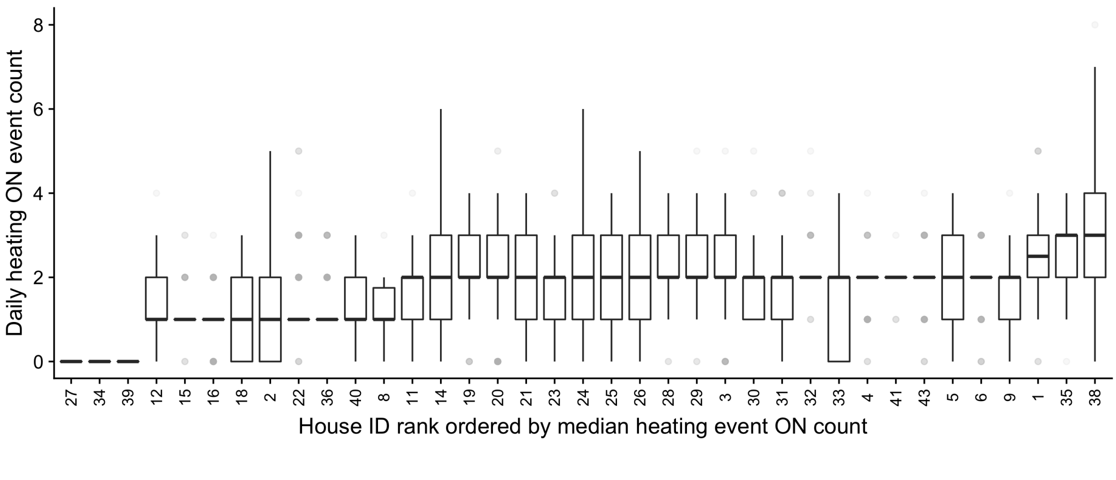

Figure 4.7: Ranked median count of living room radiator ON events for each house across the winters of 2016-17 and 2017-18. Radiators were considered as "ON" if the measured instantaneous radiator temperature was > 35°C. Consecutive ON readings are treated as a single event.

Figure 4.8 shows the median internal humidities, measured using the living room sensor, for each home across the winters of 2016-17 and 2017-18. For the first winter (2016-17) the mean relative humidity was 51.59% (s = 8.45%) and for the second winter (2017-18) the mean relative humidity was 50.37% (s = 8.75%).

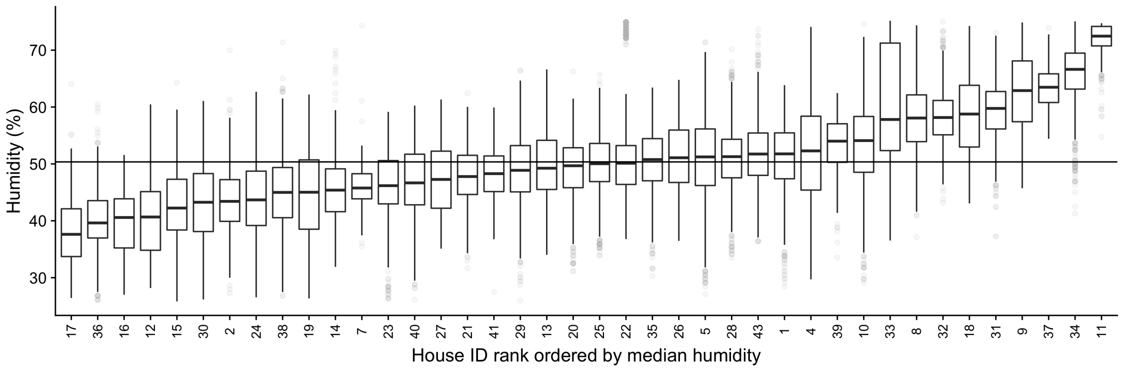

Figure 4.8: Ranked median internal living room (LR) humidities for each house across the winters of 2016-17 and 2017-18. Rooms evaluated between [0700, 2100). The black line shows the mean across all homes.

4.6.1 Thermal Comfort

In the surveys, participants responded with their Thermal Sensation Vote (TSV), which measures how comfortable they found the temperature in their home, using the widely used Bedford Thermal Comfort scale (Table 4.5).

Table 4.5: Bedford Thermal Comfort Scale.

Response	Scale
Much too warm	3
Too warm	2
Comfortably warm	1
Neither warm nor cool	0
Comfortably cool	-1
Too cool	-2
Much too cool	-3

We implemented the code to compute PMV in the statistical programming language 'R', and validated it against known input-outputs. Figure 4.9 shows that the classical PMV model consistently under-predicts the true comfort of participants. Indeed, 79% of the TSV votes are in the interval [-1,+1]. Although regressing a continuous variable (PMV) against a categorical variable (TSV) is not appropriate, the poor correlation ($R^2 = 0.28$) between the two is indicative of the scale of deviation between the two variables. This suggests the PMV model is unsuited to predicting thermal comfort in the elderly.

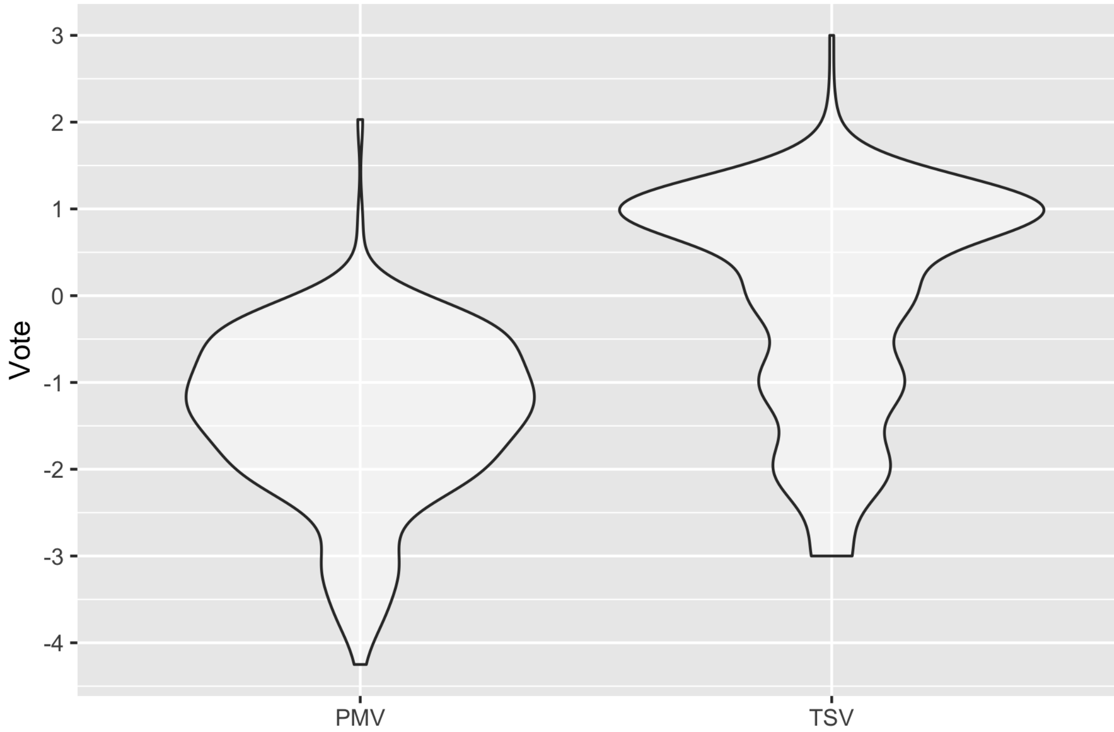

Figure 4.9: Density plots for TSV and PMV, across the winters of 2016–17 and 2017–18.

4.6.2 Health Outcomes

Figure 4.6 shows that only 30% of the participating homes are meeting the WHO recommended temperature for the elderly of between 20 and 21°C, and 70% are meeting the minimum threshold of 18°C. This is concerning as clearly homes in our sample are much colder than recommended temperatures suggest to ensure their health is maintained.

Visits to medical professionals, for instance GPs, Accident and Emergency, Inpatients, Outpatients and social care professionals, were recorded in each questionnaire. The surveys cover a total of 8 winter months (Dec → March) in each winter. There were a total of 230 valid responses out of a possible 344 (43 homes × 8 months), giving a return rate of 67%. These are plotted together with mean monthly internal and external temperatures in Figure 4.10. No clear link between low temperatures and health is apparent in these data as more low temperatures are associated with no health care visits (represented as 'N') than are associated with health care visits. Indeed most participants (83.5%) were found to be healthy (i.e. not accessing any form of care) across all months. Those who did access medical care of any kind were not found to have low internal temperatures($\overline{x} = 18.7°C, s = 2.76°C$). Although those accessing health care for respiratory problems had a lower mean temperature of 17.7°C ($n = 7, s = 1.6°C$), it is hard to conclude there is a link between temperature and respiratory health. These results indicate that minimum internal temperature recommendations may not correlate with health in the elderly, though this requires further investigation.

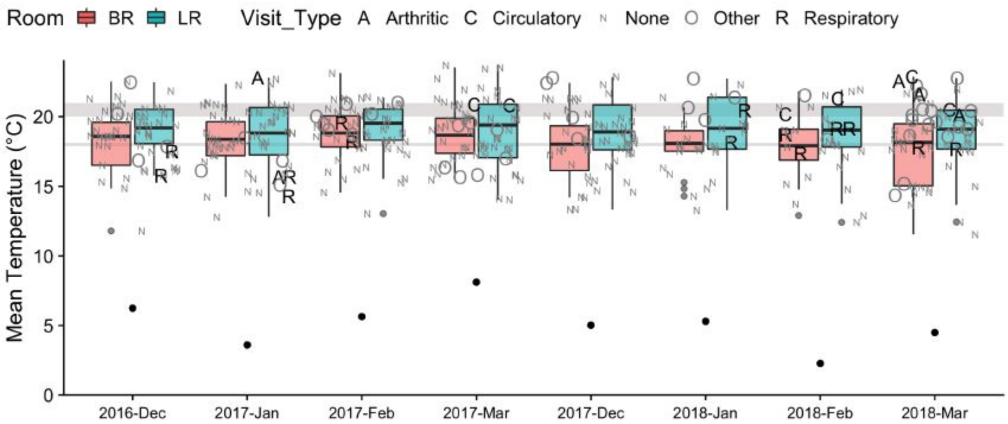

Figure 4.10: Mean internal bedroom (red) and living room (blue) temperature box plots for the winters of 2016–17 and 2017–18 in all homes. Living rooms evaluated between [0700, 2100) and bedrooms between [2100, 0700). Black dots are mean monthly external temperatures. Each letter indicates a single home against type of morbidity (Arthritic, Circulatory, Respiratory, Other) that resulted in a visit to either a GP, Inpatient, Outpatient, Social Care or Accident and Emergency. Small Ns in grey denote homes that did not access healthcare in each month. The grey band and line show WHO recommended minimum temperature for the elderly (20–21°C) and the general population (18°C).

4.7 Correcting the PMV model for the elderly

Our sample has yielded 266 valid individual thermal comfort survey responses, coincident with indoor environmental data, from a socio-economically diverse sample. This suggests that a first order correction to the PMV model for the elderly is possible. As discussed earlier, of the six traditional variables incorporated into the classical PMV model ($\mathrm{t_a, t_r, RH, V_a, CLO, MET}$), our field data allows us to eliminate $\mathrm{t_r}$ and $\mathrm{V_a}$ as independent variables, in addition to MET which is assumed rather than measured. This leaves $\mathrm{t_a}$, RH and CLO. We have two readings for $\mathrm{t_a}$ split by room: living ($\mathrm{t_{LR}}$) and bed ($\mathrm{t_{BR}}$). Since 98.8% of our survey responses came during the daytime when our respondents were primarily in their living rooms, we eliminate $\mathrm{t_{BR}}$ from the model. Each of the remaining variables is tested using the well known Akaike Information Criterion (AIC) for significance in explaining observed TSV. Since AIC estimates the relative information *lost* by a given model, lower AIC numbers represent a better model. For models using either $\mathrm{t_{LR}}$, RH or CLO we get AIC of 351, 369 or 398 respectively. All models using more than one regressor variable produce even higher AIC. Hence, we eliminate RH and CLO from our model.

Our data is longitudinal and is likely to contain (i) temporal dependencies (due to repeated sampling) (ii) interactions among the variables (e.g. between temperature and clothing) and (iii) information taken at different scales (since not all variables change in each month, e.g. $\mathrm{V_a}$). Linear mixed-effect models are ideally suited to address these challenges (Verbeke 1997).

Hence, in contrast to traditional linear models that include only the fixed effect covariates plus an error term, we propose a mixed-effects linear regression model that splits the dependent variable into 'fixed' and 'random' effect factors (covariances) to explain the independent variable. This novel approach enables the complexity of the interactions between the variables to be better reflected in the model, which consequently reduces the error (RMSE) and hence, improves model accuracy. Typically, mixed-effects models are used to describe relationships between a response variable and covariates, grouped according to one or more classification factors (Pinheiro and Bates 2009, Hartley and Rao 1967, Faraway 2016). Furthermore, one of the key benefits of a mixed-effects model approach is their applicability to hierarchical structures of variance and their ability to model any relationship through computing a wide variety of variance-covariance structures (correlation patterns). Overall, therefore, they provide better model variability assessment and enable more robust generalisation of the outputs. There are many types of mixed-error models. In this paper the fixed intercept and random slope model was chosen to account for the fact that while all the individuals in our dataset behave similarly, there is a random variation in the evolution of the linear model. Hence, a random slope model attempts to capture this average variability that specifically affects the slope but not the intercept. A mixed-effects linear model takes the following form for i=(1...m) and j=(1...n):

$$y_{ij} = \alpha + \beta x_{ij} + b_i x_{ij} + e_{ij} \tag{4.1}$$

Where:

n = number of individuals, i

m = number of repetitions per individual

y_{ij} = output based on the j-th measurement of the i-th individual.

α = fixed intercept

β = gradient of model

x_{ij} = independent variable

b_i = random slope associated with each individual $\sim \mathrm{N}(0, \sigma_{(i)}{}^2)$

e_{ij} = gaussian error term $\sim \mathrm{N}(0, \sigma^2)$

σ = standard deviation

The above expression contains separate random slopes for each individual (i) due to the repetitions (m). However, we seek a more general expression such that the random slope is the same for all individuals, which yields the following simplified model:

$$\hat{y}_i = \alpha + \beta x_i + b x_i \tag{4.2}$$

Where b is simply the random slope over the entire data set. Note that the gaussian error term is removed as the dependent variable is now an estimation (indicated as $\hat{y}_i$).

Based on this we propose an age-corrected PMV model, where the independent variable is air temperature (t_a), the error term for the slope follows a normal distribution within the interval denoted by N(0,0.3993) and the output is the predicted mean vote for the elderly (PMV_e), as shown in Equation 4.3.

$$\mathrm{PMV_e} = -4.29388 + 0.22752 t_a + \mathrm{N}(0, 0.3993) t_a \tag{4.3}$$

The RMSE for PMV_e is 40% lower (0.898), compared to the classical PMV model (1.486). Model residuals in both cases are homoscedastic, so the linearity assumption is valid (see Appendix 11) and a Shapiro-Wilk test suggests data are normally distributed ($W = 0.95799, p > 0.2$).

4.7.1 Implications of PMV_e for heating demand

A thermal comfort model implies target indoor environmental conditions that need to be satisfied for occupants to feel thermally comfortable. Since external conditions are often on either side of such targets, heat needs to be either added or removed from indoor spaces to achieve comfort – implying the need for heating and cooling systems. This energy expenditure not only increases carbon emissions, but can financially impact those on low incomes, as discussed in Section 4.3. Here, we assess the difference between predicted and actual energy consumption using two different comfort thresholds: classical PMV and our new PMV_e. These comfort models are inserted into otherwise identical thermal models of our sample homes to compare energy demand predictions. Methods are as follows:

- Thermal models for a subset of 6 homes were created in Design Builder, using data from a photographic survey. Homes were selected to provide a range of transmittances (e.g. wall U-Values range from $0.4 - 2.1 Wm^{-2}K^{-1}$), dwelling ages (40–255 years old), boiler efficiencies (60%–89%) and built morphologies (3 × semi-detached, 2 × flats, 1 × terraced).
- A Test Reference Year (TRY) for Bath was created using the method from (Eames et al. 2011) to illustrate mean winter energy consumption.
- Each model was run once with both comfort models, giving us a total of 12 simulations.

The thermal models were validated in free-running mode against known indoor and outdoor summer temperatures using NMBE and CVRMSE per ASHRAE standards (ASHRAE 2002). Table 4.6 suggests the models perform well, as both NMBE and CVRMSE are substantially under the recommended thresholds (10% and 30%

respectively).

Table 4.6: Validation of thermal models

Houses		ID1	ID8	ID11	ID23	ID28	ID36
Living Room	NMBE (%)	-1.0	+4.0	-2.5	+0.4	+2.6	-5.7
	CVRMSE (%)	5.8	5.4	3.8	2.8	6.1	7.6
Bedroom	NMBE (%)	+4.1	-4.3	-0.5	-2.9	+1.3	+3.9
	CVRMSE (%)	9.1	5.1	3.8	4.9	6.0	9.9

Five set–point temperatures were chosen for the thermal models, using the calculated probability density function from PMV_e. Figure 4.11 shows the energy consumed for each modelled home for a PMV = 0 (i.e. occupant comfort) using classical PMV and PMV_e at the 5 set–point temperatures. Figure 5 shows predicted winter heating demand using the PMV_e model against the classical model. Using the PMV_e model results in an average reduction of 44% of predicted demand (or 4,520 kWh) across the 6 homes. This could be significant, especially for low income households.

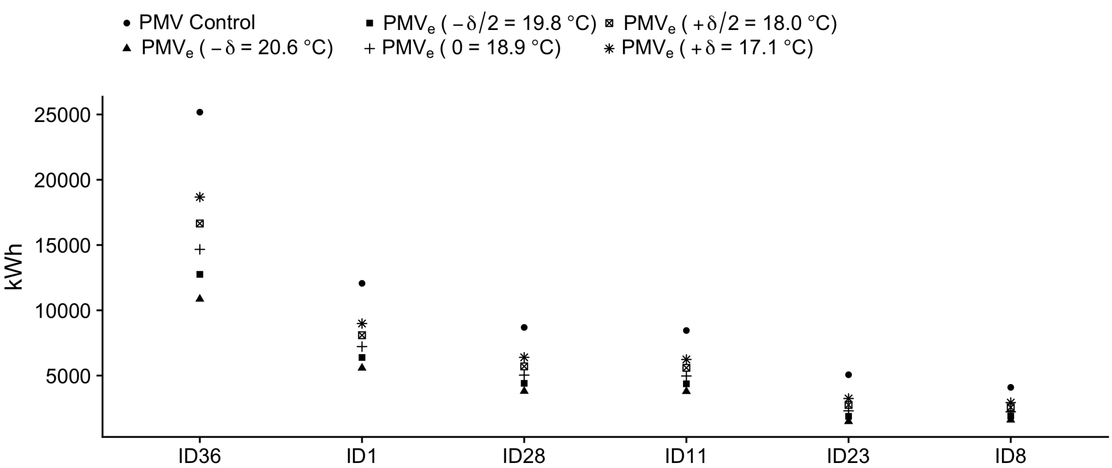

Figure 4.11: Predicted winter heating demand using classical PMV and PMV_e. ID = House ID in our sample.

4.8 Discussion and Conclusion

This paper has shown that the WHO recommended minimum temperature thresholds of 20-21°C for elderly people and 18°C for the general population, are only partially achieved in our sample since mean internal temperatures were 18.9°C and 18.2°C for living and bedrooms, respectively, across both winters. Crucially, we demonstrate that the observed temperatures are found to be broadly *comfortable* by a significant number of respondents in marked contrast to the predictions from the PMV/PPD model. In 87% of cases the self-reported TSV value was at least one vote higher than the calculated PMV value; and were between [-1, +1] in 79% of homes.

Therefore, this paper, for the first time has shown that current thermal comfort models are potentially not suitable for predicting comfort in the elderly and may, in fact, significantly over-prescribe comfortable temperatures. Our data has allowed us to derive a novel mixed-effects linear regression model (PMV_e) whose RMSE error is 40% lower than the classical PMV model. This could be used to better predict energy and comfort performance in the homes of the elderly. That the observed temperatures are broadly consistent with those of the general population observed in the literature (Table 4.2) suggests that the model may be more generally applicable, but this would require further analysis. We demonstrate the potential impact of our new model in a subset of 6 homes from our dataset, by comparing the predicted energy consumption when using the PMV and PMV_e models. This suggests a mean difference of 4,520 kWh in a typical winter, translating to a mean saving of 44% when using PMV_e.

Section 4.3 discussed the potentially harmful effects of cold homes that manifest predominantly in the 65+ demographic and lead to preventable morbidity and mortality each winter. However, there is little evidence in our data to demonstrate that low internal temperatures are having an impact on health. This requires further investigation, possibly in a larger sample, given the known strength of association between EWDs, age, temperature and health in the literature.

Overall, the findings in this paper question current assumptions around comfort and health in the elderly. This is important given that two of the most significant challenges to modern society are climate change and ageing populations.

4.9 Acknowledgements

The authors would like to thank EPSRC for their support via the EPSRC Centre for Decarbonisation of the Built Environment (dCarb, EP/L016869/1). EPSRC were not directly involved in the design or implementation of this study.

All data created during this research are openly available from the University of Bath data archive at https://doi.org/10.15125/BATH-00537.

4.10 Postscript

Results from this chapter have, for the first time, identified mean internal temperatures of homes occupied by older people, where results have shown that the participating older people are only partially achieving recommended internal temperatures. Furthermore, the participants reported to be comfortable at lower temperatures that Fanger's PMV/PPD model predicted. Hence, this chapter concluded that Fanger's PMV/PPD model is not suitable for predicting thermal comfort in the elderly and so a new model was designed to better reflect thermal comfort of older people in winter. Moreover, this chapter has shown that there is little evidence in the participating sample to link cold homes with poor health, although further research, perhaps in a larger sample, is necessary.

As participants reported feeling more comfortable at lower than recommended temperatures, despite some measured temperatures being very low (lowest recorded mean internal temperature across both heating seasons was 13.0°C) the next chapter investigates methods and strategies used by the older demographic to achieve thermal comfort in cold conditions.

Chapter 5

'The older I get, the colder I get' - older people's perspectives on coping in cold homes.

Abstract

An average of 26,560 UK excess winter deaths occur in 65+ year olds each winter, 30% of which are attributed to cold homes. Cold homes are known to exacerbate health problems prevalent in the 65+ demographic. Through conducting interviews in homes occupied by 65+ year olds known to be achieving less than the WHO minimum recommended temperature (18°C), this paper highlights their struggles in maintaining health and managing their homes, with instances of extreme and potentially dangerous methods to achieve thermal comfort identified. Fairer energy provision, better targeted financial aid and improved support networks are necessary to alleviate current problems.

Keywords: Ageing Population, Thermal Comfort, Cold Homes, Coping Strategies,

5.1 Preamble

This chapter reports the results of interviews conducted in homes not achieving the baseline 18°C temperature. Interviews were conducted in March 2018 which was unusually cold, with two instances of snow. The coldest homes were selected based on their mean internal temperature from the first phase of the project (November 2016 – March 2017). In total 11 homes did not achieve the 18°C thresholds, of which seven were available for interview. The interviews discussed the participants thermal comfort, strategies they used to stay warm and what they felt the main barriers to achieving thermal comfort were if they felt uncomfortable. This chapter specifically addresses Research Question 2 'What strategies do older people perform to reduce cold-related morbidity and enhance their comfort?'

Before the study commenced, ethical approval was obtained from the research ethics committee of the Department of Architecture and Civil Engineering at the University of Bath. All participants signed a consent form at the beginning of the interviews, where they were informed that their data would be confidential and stored in accordance with the Data Act 1998. Furthermore, they were assured that they did not have to answer anything they did not feel comfortable answering and they could withdraw from the interview at any point.

5.2 Declaration of Authorship

<table>
<tr><td colspan="10">This declaration concerns the article entitled:</td></tr>
<tr><td colspan="10">'The older I get, the colder I get' - older people's perspectives on coping in cold homes.</td></tr>
<tr><td colspan="10">Publication status (tick one)</td></tr>
<tr><td>Draft manuscript</td><td></td><td>Submitted</td><td></td><td>In review</td><td></td><td>Accepted</td><td></td><td>Published</td><td>✓</td></tr>
<tr><td>Publication details (reference)</td><td colspan="9">Caroline Hughes and Sukumar Natarajan (2019)'The Older I Get, the Colder I Get'- Older People's Perspectives on Coping in Cold Homes, Journal of Housing For the Elderly, DOI: 10.1080/02763893.2019.1567642</td></tr>
<tr><td>Candidate's contribution to the paper (detailed, and also given as a percentage).</td><td colspan="9">The author of this thesis has primarily contributed to defining the methodology, conducting the interviews and writing the manuscript.

C Hughes: Formulation of Ideas (90%); Design of Methodology (90%); Data Collection (100%); Data Analysis (90%); Preparation of Manuscript (90%).

S. Natarajan: Formulation of Ideas (10%); Design of Methodology (10%); Data Analysis (10%); Preparation of Manuscript (10%)</td></tr>
<tr><td>Statement from candidate</td><td colspan="9">This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.</td></tr>
<tr><td>Signed</td><td colspan="5"></td><td>Date</td><td colspan="3"></td></tr>
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5.3 Introduction

In recent years there has been increasing concern over how the elderly stay warm in winter within their homes (Wright 2004, Chard and Walker 2016, Day and Hitchings 2011, O'Neill et al. 2006*b*). They are construed as vulnerable (Chard and Walker 2016, Christensen et al. 2009); often struggling to keep warm as a consequence of inadequately maintained housing (Hamza and Gilroy 2011, Romero-Ortuno et al. 2013) and inaccurate health beliefs (Wright 2004, Day and Hitchings 2011, Gascoigne et al. 2010). Existing studies of older people's practices in winter focus on those exclusively in fuel poverty (Chard and Walker 2016, O'Neill et al. 2006*b*), with the debate centering around government incentives to alleviate this problem (Wright 2004, Critchley et al. 2007). Nearly a third of fuel poverty sufferers are aged 65 and over (Wookey et al. 2014), highlighting the clear need for such research. However, the 10 year UK mean Excess Winter Death (EWD) rate is 26,560 per year in the 65+ demographic (ONSCensus 2018), of which only 10% occur in fuel poor homes (Wookey et al. 2014). Although the EWD figure is a small proportion of the number of 65+ year olds (0.2% of total 65+ population), it represents the most severe examples. There are believed to be many more older people suffering cold related morbidity, but the extent of this is not fully understood (Ansari and El-Silimy 2008). In fact, EWDs tend to be more prevalent in affluent areas (Wookey et al. 2014), likely in large, old homes that are difficult to heat. Cold homes are estimated to be responsible for 30% of EWDs (Geddes et al. 2011), with research showing that occupiers of the coldest 25% of homes have a 20% higher risk of dying during the winter months, compared to those in warmer homes (Wilkinson et al. 2001). It is important, therefore, to recognise that a high income does not definitively result in a warm home.

Health implications of exposure to prolonged periods of cold are widely documented and are said to be most clearly apparent in older people (Donald 2009). Low temperatures are known to exacerbate cardiovascular and respiratory problems, the two leading causes of EWDs (Healy and Clinch 2004, Kumar et al. 2016). Following a period of cold weather, Accident and Emergency (A&E) and GP visits increase dramatically (Elliot et al. 2008). For every degree that external temperature decreases below 5°C there can be as much as a 19% increase in the number of consultations held with older people suffering respiratory problems (Hajat et al. 2007). Concerningly, older people are most at risk of cold related morbidity and mortality due to a diminished metabolic and vasoconstrictive rate, caused by biological ageing (Day and Hitchings 2011). This is often further complicated by the fact that older people are said to be less capable of recognising temperature changes and consequently less likely to make necessary changes to their environment to protect their health (Critchley et al. 2007, Wookey et al. 2014). At present cold home related morbidity and mortality in older people is estimated to cost the NHS in excess of £1.3 billion per year (i.e. around 1% of the total 2017–18 budget, (Burlinson et al. 2018)). As demands on the NHS increase (Christensen et al. 2009), it is imperative that people can live at home for as long as possible free from the threat of hospital admission through cold-related morbidity.

Furthermore, by 2050 it is predicted that over 25% of the UK population will be aged 65 and over (Wouters 2017, Riley 2005), most of whom will spend long, largely sedentary, periods in their homes (Havenith 2001). It is estimated that septuagenarians spend 85% of their time at home, which rises to 95% for octogenarians (Hamza and Gilroy 2011). The thermal efficiency of UK dwellings is known to be poor (Rudge and Gilchrist 2005), and older people are said to be least likely to conduct regular home maintenance and install retrofit measures, which are known to improve efficiency (Hamza and Gilroy 2011, Donald 2009). Consequently, there are an increasing number of older people spending long periods of time in sub-optimally heated homes, raising concerns over their health (O'Neill et al. 2006*b*, Romero-Ortuno et al. 2013, Hamilton et al. 2017).

Minimum internal temperature recommendations have existed for over 30 years, with the key aim of maintaining occupant health. The WHO produced the basis for the recommendations, identifying that homes should be heated to a minimum of 18°C, with an elevated requirement for 20-21°C in homes occupied by older people (WHO 1987). These recommendations have informed UK Government policy (Wookey et al. 2014) and Age UK guidance (AgeUK 2018*b*), albeit with the adaptation of 20-21°C in the most used rooms only, not the entire house. It is unclear, however, how many older people achieve these internal temperatures and what older people do to achieve comfort in their homes.

5.4 Literature Review

Despite assumptions around the contributing factors, there is little evidence to show that EWDs increase with colder climate (R. de Vries 2012), low socio-economic group, insecure tenure or low number of occupants (Wilkinson et al. 2004). It is also important to recognise that EWDs are the most severe example of cold related illness endemic in 65+ year olds in the UK. In fact, for every EWD there are estimated to be at least eight cold-related hospital admissions (Roche 2010). It is clear that more older people than literature recognises are likely to be suffering in cold homes. The need for qualitative research highlighting people's actions to keep warm in cold weather has been identified in several studies (Jevons et al. 2016, Guy et al. 2015, Hernandez 2016), especially the actions of older people (Miller et al. 2017, Healy and Clinch 2002). To date there have been a small number of qualitative studies, summarised in Table 5.1. Although half of the studies do focus on older people, they are either on all female subjects (O'Neill et al. 2006*b*), focus on fuel poverty (Wright

2004, Chard and Walker 2016, Day and Hitchings 2011), or investigate the impact of retrofit interventions (Devine-Wright et al. 2014). Given that it is suggested only 10% of EWDs occur in fuel poor homes (Wookey et al. 2014), there are likely many more older people suffering cold homes who do not classify as fuel poor, but this is not clearly understood (de Chavez et al. 2017).

Table 5.1: Summary of qualitative research on cold homes and fuel poverty.

Paper	Year	Location	Number of Participants	Demographic	Analytic Method	Key Findings
Wright (Wright 2004)	Spring '03	England	64	60–90		Heating system was often old and ineffective, but no grants available for homeowners to modernise them. Cultures of living among the elderly contributes to their cold homes e.g. common practice to sleep in unheated bedrooms and keep the window open during winter.
O'Neill (O'Neill et al. 2006*b*)	Winter '05–'06	North Wales	17	55+	Grounded Theory	Older women find it difficult to keep homes warm and frequently economise on food to heat homes.
Walker (Walker et al. 2014)	Nov-Dec '08	Sunderland, UK	26	All Ages	Grounded Theory	Critical for occupants to understand new technologies post-retrofit to ensure energy savings. Habit plays a significant part in occupant actions, eg. participants still used fireplaces despite retrofitting.
Day (Day and Hitchings 2011)	Winter '08-09	Birmingham, UK	21	65+	Thematic Analysis	Current ideas of ageing are based on chronological ageing, constructing a stigmatised view that is not accurate for all older people and leads to them resisting advice. Older people recognise that their warmth preferences have changed as they aged, but they do not feel they are suffering.

Hitchings (Hitchings and Day 2011)	Winter '08-'09	Birmingham, UK		70+		Participants rarely considered generational attitudes to warmth and did not identify with the image of an older person struggling in winter. Respondents had a limited understanding of what other older people do to stay warm in winter.
Anderson (Anderson et al. 2014)	Oct-Nov'09	Great Britain	50	All Ages		Participants who lacked finances to heat home used only one or two rooms. Pensioner households were more likely to ration heating than working age households. For lowest incomes retrofitting did not eliminate the risk of cold homes as any heating was difficult to fund. Personal resourcefulness and coping skills were very apparent to maintain quality of life.
Mould (Mould and Baker 2017)		Scotland	887	All Ages		Fuel poverty metrics are said to be inadequate for reaching the most vulnerable.
Middlemiss (Middlemiss and Gillard 2015)	2010 and 2013	UK	17 (7 in 2010 and 10 in 2013)	20–69	Grounded Theory	Recognised six key challenges to fuel poor households: quality of dwelling fabric, tenancy relations, energy costs and supply, stability of households income, social relations and ill health. Recognise that respondents have limited ability to face the six key challenges.

Chard (Chard and Walker 2016)	Winter '12 –'13	England	17	55+	Grounded Theory	Participants did not feel vulnerable, viewing their actions to keep warm as common sense. Question over what actions are acceptable to achieve comfort (eg. wearing outdoor clothes indoors).
Devine (Devine-Wright et al. 2014)		UK	104 in 31 different buildings	55+	Thematic Analysis	Cosiness and glow important for older people, they need to see and feel warmth manifest in multiple ways (eg. fireplace).
Grey (Grey et al. 2017)	March '14 and March '15	Wales	22	All Ages	Thematic Analysis	Risk factors (eg. inefficient homes and expensive fuel) contributed to poor physical and mental health, financial stress, social isolation and the heat-or-eat dilemma.

Our review suggests that the main strategies for keeping warm among this demographic are:

(i) including additional clothing (Chard and Walker 2016, Day and Hitchings 2011, Anderson et al. 2014)

(ii) extra sources of heat (e.g. hot water bottles and blankets) (Day and Hitchings 2011, Anderson et al. 2014)

(iii) altering patterns of behaviour (e.g. staying in bed longer) (Day and Hitchings 2011, Anderson et al. 2014)

(iv) using secondary heating (Chard and Walker 2016, Walker et al. 2014, Anderson et al. 2014), (worryingly in one instance use of the oven as the only heat source (Hernandez 2016))

(v) having hot drinks (Anderson et al. 2014) and

(vi) exercising (Day and Hitchings 2011, Anderson et al. 2014).

Fuel rationing was commonplace (Wright 2004, Chard and Walker 2016, Day and Hitchings 2011, O'Neill et al. 2006*b*, Anderson et al. 2014, Grey et al. 2017), especially in retired households (Anderson et al. 2014), where heating is often found to be limited to certain times and rooms. In extreme situations this results in living, eating and sleeping in the same room (Grey et al. 2017), or choosing between food and heating – the heat-or-eat dilemma (O'Neill et al. 2006*b*, Anderson et al. 2014, Grey et al. 2017, Monroe et al. 2007).

The impact of cold homes on physical health is well documented (Donald 2009, Healy and Clinch 2004, Kumar et al. 2016, Webb et al. 2012), but the literature also highlights the negative impact cold homes can have on mental health. Said to be due to social isolation (Devine-Wright et al. 2014, Grey et al. 2017), lack of financial means, poor housing condition and the subsequent condensation, damp and mould that is common in cold homes (Grey et al. 2017).

Energy efficient retrofitting is one method used to improve the thermal performance of the building, reducing energy consumption and thus heating bills. Although such interventions are said to improve both physical and mental health (Anderson et al. 2014, Shortt and Rugkasa 2007), through increases in internal temperatures (Oreszczyn 2006), older people's interaction with retrofitting is less well understood. Habits of older people are said to influence their expectations of thermal comfort (Walker et al. 2014), with studies finding that older people preferred visible heat sources (eg. fires) above invisible sources (eg. underfloor heating) (Devine-Wright et al. 2014).

There is a need for better understanding of older people's experiences in their homes (Miller et al. 2017, Hayashi et al. 2017), especially in trying to stay warm and healthy (O'Neill et al. 2006*b*, Harrington 2005, Reid 2015). Assumptions are often made that older people are attached to outdated methods of doing things (Wright 2004, Harrington 2005), are not always compliant with modern methods (Day and Hitchings 2011) and try to cope or 'make do' with their current situation even when it is unsuitable (Chard and Walker 2016).

There is a clear gap in research of how older people manage to stay warm and well in cold weather, if indeed they are managing, as well as whether the assumptions made about them are true, and if so, then why this is the case. It is crucial to document the experiences, opinions and patterns of behaviour of older people to better understand their situation and tailor policy and incentives to enable their health and independence. Hence, this paper addresses the following key research questions:

1. What strategies do older people implement to keep comfortable during cold periods?

2. If uncomfortable, what prevents them from being able to achieve comfort?

5.5 Methods

5.5.1 Study Context

This paper forms part of a wider longitudinal monitoring study focusing on the thermal conditions in the homes of 43 participants all aged 65 and over and living in Bath, UK. Between November 2016 and September 2018 four phases of data collection were undertaken (November 2016 - March 2017; June 2017 - September 2017; November 2017 - March 2018 and June 2018 - September 2018) to measure the internal temperatures of the 43 homes. There were two methods used in participant recruitment. A letterbox drop of 600 leaflets in the 12 wards of Bath recruited 25 participants and the remaining 18 were recruited through talks given to Age UK, St. John's Care in Bath, U3A and Transition Bath. Sensors were placed in the living room, bedroom and on the living room radiator and set to record the temperature at 90 minute intervals for the duration of each phase. Corresponding monthly questionnaires were sent throughout the phases of the project capturing demographic data, housing characteristics, heating practices, thermal comfort and health data.

The results of the temperature monitoring are reported extensively in another paper, but are briefly reported here for context. Figure 5.1 shows internal living room temperatures of each home, ranked by median temperature, for the two winters monitored in the study (November 2016 - March 2017 and November 2017- March 2018). The significant amount of information collected over the two year period provided an excellent context in which to conduct interviews in a subset of the coldest homes to explore in more detail how the participants dealt with the cold. All homes from the monitoring period between November 2016 and March 2017 whose average internal temperatures were below the WHO threshold of 18°C (WHO 1987) (identified with a box in Figure 5.1) were considered for interviews, to investigate what strategies they use to stay warm and what reasons there are, if any, that prevent them from attaining comfort.

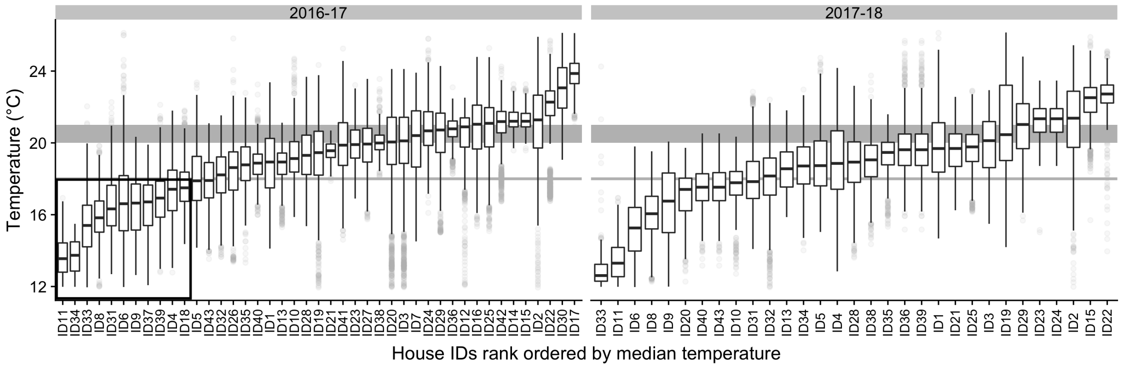

Figure 5.1: Ranked median internal living room temperatures for each house across the winters of 2016-17 and 2017-18. The grey band shows the WHO suggested minimum threshold internal temperatures for the elderly (20-21°C), and the grey line shows the minimum recommendation for all homes (18°C). Homes included in the black box (under 18 °C) in the 2016-17 graph were selected for interviews.

Of the 11 homes recording 18°C or lower, a total of seven were interviewed (two were omitted due to ill health and two due to unavailability at the time of the interviews). Table 5.2 shows the characteristics and heating practices of the participants.

Table 5.2: Participant characteristics and heating practices

Participant ‡	**Age**	**Gender**	**Occupants**	**Income**	**House Type ◇**	**House Age (years)**	**Number of Chronic Illnesses**	**Central Heating Patterns ***	**Secondary Heating (Gas Fire)**	**Daily Hours at Home**
Catherine	68	F	1	Low	SD	60	1	1A		16
Gladys	71	F	1	Low	SD	90	• 2	2A		20
Jennifer	74	F	1	Low	F	233	• 5	1B	Yes	20
Elizabeth	72	F	1	Medium	SD	40	• 2	1A		18
James	66	M	1	Medium	T	121	• 1	2B		16
Anne	82	F	1	Not Sure	SD	73	0	ø	Yes	22
Susan	74	F	1	Low	SD	57	• 1	2A	Yes	20

Notes:

All homes were owner occupied by a single occupant.

‡ names have been changed to ensure anonymity.

◇ SD = Semi-detached, T = Terrace, F = Flat

• Denotes participant has one or more of chronic arthritis, respiratory problem or circulatory problem.

ø participant did not have central heating.

* 1A= heating is on once per day, between 4pm and 9pm; 1B = heating is on once per day between 9pm and 10pm; 2A = heating is on twice per day, between 7am and 10am then between 5pm and 7pm; 2B = heating is on twice per day, between 7am and 1pm and 5pm until 10pm.

5.5.2 Internal temperatures and heating patterns in the selected homes

The temperature profiles of our selected homes are shown in Figure 5.2. Heating duration per day over the selected homes equalled on average 4.64 hours (SD=2.55), compared to an average of 8.29 hours over the entire participant sample of 43 homes (SD=4.51), showing that on average the coldest homes had the heating on for only about half the time of the non-coldest homes.

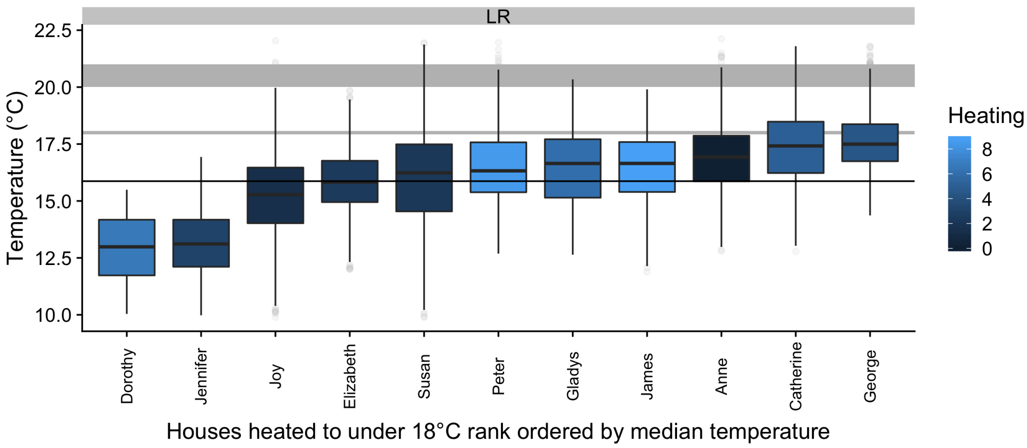

Figure 5.2: Ranked median living room (LR) temperatures for each house across the winter of 2016-17 evaluated between [0700, 2100). The grey band shows the WHO suggested minimum threshold internal temperatures for the elderly (20–21°C), the grey line shows the minimum recommendation for all homes (18°C), and the black line shows the mean internal temperature across all 11 homes (15.87°C). The colour scale shows the number of hours of heating per day.

Older people are said to need longer periods of heating, due to long periods spent at home (Kane et al. 2015), but this was, unsurprisingly, not observed in our sample of the coldest homes (Table 5.2 and Figure 5.2). Most participants had either one (non-continuous) or two heating patterns per day, in line with findings of other studies (Kane et al. 2015, Huebner, Cooper and Jones 2013, Huebner, McMichael, Shipworth, Shipworth, Durand-Daubin and Summerfield 2013*a*). Although none of the interview participants interviewed met the WHO recommended temperatures, some self-reported as thermally comfortable, which raises an interesting question over the extent to which current guidance information is suitable. Similar to findings of other studies (Critchley et al. 2007), an ethical dilemma arises that if healthy occupants are comfortable at low temperatures, should they be encouraged to increase it? Raising internal temperatures in the current climate, which is heavily focused on reducing space heating consumption could be paradoxical.

5.5.3 Method Selection

Most studies of a similar nature use either Thematic Analysis (Day and Hitchings 2011, Devine-Wright et al. 2014, Grey et al. 2017) or Grounded Theory (Chard and Walker 2016, O'Neill et al. 2006*b*, Walker et al. 2014, Middlemiss and Gillard 2015) to code and analyse data (see Table 5.2).

This method was chosen as it enables understanding of the participants perspective to be gathered, identifying themes and patterns about older people's coping strategies and challenges in cold weather to emerge from the data. Grounded theory, although sometimes used in similar studies, was not chosen as it requires either the creation of a theory from the data, the representation of reality (Positivist Grounded Theory) or acknowledges that the researcher will shape the data and thus argues there is not one 'accurate' reading of the data (Braun and Clarke 2012).

Using Thematic Analysis, our goal was to ascertain the ways in which older people managed to stay warm in winter and how their attitudes, opinions and everyday practices affected this. This was undertaken using semi-structured interviews, conducted in March 2018. This period, fortuitously, experienced unusually cold temperatures, with two spells of snow. By this point the author had been visiting the participants every three months for over 18 months, so had built good relationships and rapport with the participants which enabled potentially sensitive topics to be discussed in the interview (eg. health problems, income).

5.6 Thematic Analysis

All the participants for this article live alone, mostly in semidetached houses and on low incomes (see Table 5.2 for further information) Overall, the analysis of our sample resulted in consideration of thermal comfort and health, strategies to deal with the cold, energy provision, and energy-efficient refurbishment, each of which is presented next. (i) thermal comfort and health (ii) strategies to deal with the cold (iii) energy provision and (iv) energy efficient refurbishment; each of which is presented below.

5.6.1 Thermal comfort and health

The widespread concern for older people in winter is a consequence of their physical ageing, which exacerbates vulnerability to the effects of the cold. In this study, most participants (88%) felt the cold more than when they were younger and had started to notice this in their late 50s and early 60s, which is concurrent with other studies of a similar nature (Day and Hitchings 2011).

The interview started by asking whether the participants were comfortable with the internal temperature in their homes, to which all but one replied yes, although for half of those who said yes, there was a clear sense that they found it bearable but not ideal:

> Catherine: Yes, I'm sure it could be better, but um, yes.
>
> James: Not always, no. I seem to have a bit of a draught problem, so literally it depends on where the wind's blowing from.

> Jennifer: I put up with it, I wouldn't say I'm comfortable, but I put up with it. I just think well if I'm cold I've got to do something about it to keep warm, it's no good if I moan to you or my friends, because they can't do anything about it.

Health is known to have an impact on EWDs, especially cardiovascular and respiratory problems. Table **??** shows that the participants had a range of chronic health problems. All participants recognised that low temperatures were potentially harmful to their health, reporting that the cold worsens health conditions:

> James: This year from mid-December onwards, I've been almost clear of it [osteoarthritis] and I thought I've really got away with it this year, but I've now got quite nasty pain in the left leg, all the way up and down it.

> Jennifer: My asthma is chronic, and I do feel that as I get older my lung function deteriorates and the cold does exacerbate it, but I manage.

> Anne: I have got some arthritis, I've had injections in both knees now. It doesn't worry me too much, but I think if there's a change in temperature and it gets wet or cold then it can make a difference [to pain levels].

There is a clear stoicism attached to managing physical health, through participants claiming they cope. Persistent cold is also said to have a negative impact on mental health (Allmark and Tod 2013), which was not overtly discussed, but did arise in two instances:

> Catherine: 'I don't think I make myself miserable with the amount of heating I have.'

> Jennifer: 'I do consciously sort of mind my own well being. But I do get fed up with wrapping myself in blankets because the one I have is a very long one and I often trip over it, I have to be so careful.'

5.6.2 Strategies to deal with the cold

Section 5.4 highlighted the coping strategies used by older people in cold weather. The five strategies found in this study correspond well with other studies, with four out of five strategies in this paper matching those in the literature review. Physical alterations made to the home to improve comfort has not previously been identified as a strategy.

5.6.2.1 Clothing

The literature showed that a frequently used strategy was to add clothing layers (Chard and Walker 2016, Day and Hitchings 2011). For the most part this is an acceptable adaptation to an environment, however, in certain cases this can include the routine wearing of outdoor clothing indoors (Anderson et al. 2014). In this study all participants added layers of clothing, in common with findings of other studies (Chard and Walker 2016). A range of items were used, from simply either a scarf or slippers to regularly wearing four layers:

> James: As far as I'm concerned I'm almost dressed for the outdoors.

> Gladys: I don't take many chances!

Almost all participants reported that they would put on extra clothing rather than turning up the heating, for most this is due to cost consciousness, but habit also pays a significant part:

> Susan: At my age I suppose I'm economical with everything and it's what I always used to do. We'd just put on more clothes, so I suppose I'm in the habit of it.

> Anne: It's funny isn't it, I suppose I just think oh it's cold today, I'll put this on. Turning up the heating isn't something I would think of.

Whilst most studies of a similar nature also found that participants seemed accepting of adding layers (Chard and Walker 2016), others found that although some older women did add layers for comfort, they were embarrassed to admit this, fearing they could seem old fashioned (Day and Hitchings 2011). Interestingly, while additional clothing seemed acceptable for participants in this study, use of personal heat sources did seem to elicit feelings of age related stigma and embarrassment.

> Elizabeth: I don't possess a hot water bottle or anything.
>
> Anne: No I never use a hot water bottle or blankets downstairs or anything like that. I've never done that, no, no.

Whilst adding another layer or wearing slippers, and using blankets are widely considered acceptable alterations to one's indoor environment in pursuit of achieving comfort, this raises an ethical question over the point at which adaptive actions become unacceptable.

5.6.2.2 Movement

Within the literature conducting exercise or movement to stay warm was not particularly common, with only one of the studies reporting it (Anderson et al. 2014). This is likely because many older people have mobility issues and movement as a strategy is therefore neither practical nor suitable. In this study one of the participants regularly moved when she felt cold.

> Jennifer: If I felt cold, I wouldn't put the heating on, I would just pick up the hoover and start hoovering around or move furniture or dance.

Older age frequently impairs mobility, meaning this strategy is not suitable or safe for a vast number of older people. This highlights that some strategies used might not be considered culturally acceptable and raises another ethical dilemma over what and when interventions should occur to ensure that the elderly do not feel the need to move furniture to stay warm.

5.6.2.3 Additional sources of heat

Use of sources of heat, such as gas fires or blankets and hot water bottles were commonly used strategies in the literature (Chard and Walker 2016, Day and Hitchings 2011, Anderson et al. 2014). In this study additional sources of heat were used, albeit infrequently. Three participants had supplementary gas fires that were rarely used:

> Catherine: It's been on maybe twice this winter.

Blankets and hot water bottles were used regularly by two participants:

> Jennifer: I've got a blanket and I tend to wrap myself up and I put a hot water bottle on my body and one on my feet and I put my feet up and then I can be comfortable for up to 4 hours.

5.6.2.4 Physical alterations to the home

Physical alterations to the home were not apparent as a coping strategy in the literature, but was used by one participant in this study. James' home is a draught prone Victorian terrace.

> James: I have a screen there, that is to protect me... because I was getting a particularly nasty cold draught which was making my ear go numb.

> James: I've had to tape up the bathroom window this winter, because when it was very cold and the cold wind was coming from the east, I put my finger up to it and it was like there was an arctic gale blowing past.

This suggests energy saving measures such as draught proofing and insulation would positively impact the participants' thermal comfort.

5.6.2.5 Creating alternative routines.

Older people are known to adapt behaviours in their home to achieve thermal comfort, for example reconfiguring rooms or alternating between main rooms (Tweed et al. 2015, Grey et al. 2017). However, within this study only two participants altered their daily routine to account for the cold weather. For Jennifer these decisions were based on consuming the lowest amount of energy to reduce cost whereas James owns a difficult house to heat. Jennifer frequently stays in bed for long periods, after waking up she has a cup of tea and reads in bed:

> Jennifer: I have occasionally dropped my teacup to make tea, because the kitchen is freezing and the heat against my hands means they don't work so well.

Although space heating was her primary concern, Jennifer also has strategies for heating water as infrequently as possible:

> Jennifer: When I boil hot water I always put it in a thermos flask, so I can drink that without warming up the kettle again. Then with the hot water bottle from the night before, I use it to do the washing up.

Furthermore, as her house is especially cold to sit and read in:

> Jennifer: Once a week I will go to the library and sit in there for 4 hours.

James finds that due to the age of his house it becomes difficult to make it any warmer and as a result spends time in the smallest bedroom when the weather is particularly cold.

> James: I think the problem is that I don't think it's actually possible to

> raise the temperature in here much more, because of the age.

5.6.3 Energy Provision

Another prevalent theme running through six of the interviews was the cost associated with domestic energy and the difficulties in obtaining a fair deal, which has been recognised in other studies (Anderson et al. 2014). The discussion of energy providers elicited only negative feelings ranging from confusion to panic to anger. It was commonly known within the group that switching energy providers yearly enables the cheapest prices to be found, however, there was unanimous agreement that this was a struggle for the participants and energy companies do not provide suitable clarity;

> Catherine: It's just so intricate, it's not easy to swap, it's like with insurance policies, when you think oh well is that included in that, so have I got a better deal or haven't I.

> Gladys: I can't understand their bills and I can't understand how they're billing me, I'm completely confused, so I don't even try and understand it now.

There was a general feeling that being advised to conduct everything over the internet does not cater for older generations and puts them at a disadvantage which concerns them;

> Susan: We feel a bit inferior, definitely. Definitely, we don't feel as secure as we were years ago.

This causes unnecessary worry for older people, who are at risk of being overcharged because of a lack of understanding about modern methods. This can increase feelings of powerlessness to change the situation and incite feelings of anger, panic and fear in relation to the knowledge that money could be saved if they felt confident in switching provider.

It was an overtly discussed theme that having to organise energy provision causes stress:

> Susan: it's just a hassle to have to think "oh no, I've got to get on the phone again", and their systems change and you can't remember what to do and you just panic. I know lots of people my age, and they, if they were here now they'd be saying exactly the same, that it causes them more anguish getting on the phone every couple of years and getting the contract sorted and what have you, it causes more hassle [than staying with their current, more expensive, provider]. I make myself call them out of anger, not out of fear but anger, how dare you put us through this.

Thoughts of the anguish associated with energy provision provoked the discussion of the support networks for older people. Older people do not feel that suitable support is in place for them to address any queries.

> Susan: We did have Age Concern here, but they've closed it, the information and the insurance and anything we need help with, they've closed it. We need a hub of people like that who we could key into without feeling embarrassed.

> Catherine: I wish I had an advisor to come and do things for me and tell me "oh this is better" because to compare like for like is very difficult [when discussing different energy providers].

> Susan: If you could get the Government to say that anyone over the age of 75 is going to be on the same electric tariff and the same gas, whoever they're with, that would be absolutely brilliant.

Given that affordable warmth is essential to maintain health (Burholt and Windle 2006), especially in older people, enabling them to achieve this should be a policy priority.

5.6.4 Energy efficient refurbishment

It is frequently assumed that older people are unwilling or incapable of taking up modern technologies, due to a lack of understanding, disinterest, fear and associated cost (Critchley et al. 2007, Gibbons and Singler 2008, Tartarini et al. 2017). Furthermore, older people are believed to be fixed in their attitudes (Day and Hitchings 2011) and have different heating expectations stemming from childhood experiences (Gibbons and Singler 2008, Devine-Wright et al. 2014) meaning they are not a focus of current retrofit schemes (Hitchings and Day 2011). It has been recognised within literature that there is a lack of understanding about how older people interact with new technology (eg. a new boiler) (Devine-Wright et al. 2014), including how capable and willing they are of adapting to a new system. Retrofitting is likely to have a positive impact on thermal comfort and health (Hamilton et al. 2015, Hong et al. 2009), potentially resulting in the rebound effect meaning that predicted energy savings would not be realised. Although this is likely to have a negative impact on fuel consumption these losses should be balanced against the likelihood of reduced cold-related morbidity due to warmer homes which, in turn, may reduce costs overall healthcare costs for society.

Unlike other studies (Chard and Walker 2016, Middlemiss and Gillard 2015), 88.5% of participants in this study reported that they would be willing to incorporate retrofit measures or new technologies in their homes, but there were some barriers, including cost and the fear of lack of control.

> Gladys: Yes, but not all these things in the house, I don't fancy getting

> my house all electronically managed. Like Hive and things like that, I saw an advert on TV where it organises everything, and I don't like that.

> Catherine: I don't like the idea of, um, turning your things on from your mobile phone, I don't like that at all.
> Interviewer: How come?
> Catherine: I don't know, it's just anti-technology I suppose. Too much technology.

Others were theoretically happy to retrofit their homes, but recognised that the associated cost renders it unaffordable.

> Jennifer: Well, for it you need the financial resources, which is something I don't have.

Others felt that at their age it was not worth it.

> Susan: Well, I wouldn't now, not at my age.

Generally, most of the participants seemed more willing to retrofit than literature would suggest, but there are clear barriers of insufficient finances and perceived loss of control. However, their reticence is potentially surmountable with financial aid and dedicated education strategies, which could be incorporated into government policy. It is clear, however, that a re-education of older people is necessary as the idea of retrofitting was not something that the participants had considered, despite not being averse to it. Other comparable studies have found similar results (Chard and Walker 2016), in that while the participants recognised they could make adjustments to their clothing and actions, the idea of making alterations to their home was not readily apparent until overtly asked.

5.7 Discussion and Conclusion

There was a clear sense of stoicism in the participants, none felt their situation was unfair despite recognising that it could be better, accepting that they used common sense to alter their environment as best they could to achieve comfort, which is consistent with other studies (Day and Hitchings 2011, Wolf et al. 2010). It is clear that older people’s mentality and habits do have an impact on their thermal comfort, and in line with other studies there is a virtue associated with frugality that is perhaps not so readily prevalent in younger generations (Chard and Walker 2016, Gibbons and Singler 2008). This is not necessarily a positive, as it renders some older people in situations that are not good for their health and well-being, but there is no obvious way for them to rectify their situation.

It is clear that older people do struggle in cold homes and in certain instances have extreme methods of ensuring they can achieve a bearable temperature. Given the ageing population there is likely to be an increasing number of older people needing support in ensuring they can achieve a fair deal for fuel and access necessary benefits. Finding energy providers was unanimously disliked and feared with calls for a specific over 75-year-old tariff made, which participants felt would be hugely beneficial to the welfare of older people.

Furthermore, better targeting of financial aid and benefits could alleviate some suffering. Although certain aids are in place, such as the Winter Fuel Payment, it is known that up to 80% of this is wasted on homes that do not struggle to afford sufficient heating (Boardman 2010). Readdressing this imbalance to ensure those most in need of financial aid are met with enough assistance to achieve adequate heating is hugely important.

This study has shown that older people are not as opposed to energy efficiency measures as literature suggests (Critchley et al. 2007). Therefore, another possibility could be retrofit schemes that exclusively focus on older people, as improving the condition of older people's homes would reduce the numbers struggling to afford heat.

There are clear methods that could be adopted which would assist in enabling more older people to achieve comfort in winter, protecting their health, well-being and independence. With an ageing population it is crucial that these methods are acted on.

5.8 Acknowledgements

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5.9 Postscript

Results from this chapter have shown that some older people do struggle to maintain thermal comfort in their homes, with instances of extreme and potentially dangerous strategies to cope exhibited in the interviews. Nonetheless, there was a clear sense that the mentality of the participants meant they coped as best they could, fearing being a burden on either the NHS or relatives.

Clear boundaries of not wanting to switch energy providers was unanimous, with lacking understanding and feeling like they might be overcharged cited as reasons for this. Furthermore, better targeting of financial assistance was another method discussed to relieve some suffering.

The next chapter moves away from coping in cold conditions onto how older people fare in summer periods, through conducting temperature monitoring throughout one typical and one extreme summer.

Chapter 6

Summer thermal comfort and health in the elderly

Abstract

Atypically warm summers such as 2003 and 2018 are predicted to become normal by 2050. If current climate projections are accurate this could cause heat-related mortality to rise by 257% by 2050, the majority of which will be in vulnerable groups such as the elderly. However, little is known about the temperatures achieved in the homes of the elderly even in typical summers, and even less on whether these are comfortable. This study examines, for the first time, the validity of current thermal comfort models in predicting summer comfort levels in the 65+ demographic over a typical and an atypically warm summer. This was achieved through the first longitudinal study of thermal conditions in homes of the elderly in the South West UK, utilising repeated standardised monthly thermal comfort and health surveys with continuous temperature monitoring in both living (LR) and bed rooms (BR). Results show that neither the PMV/PPD model (ISO 7730) nor the adaptive model

(ISO 15251) accurately predict true thermal comfort in our sample. Overheating analysis using CIBSE TM59 (based on ISO 15251) suggests significantly more homes (50% LR, 94% BR = 94% overall) overheated during the atypically warm summer, compared to the typical summer (3% LR, 57% = 57% overall). These are worrying results, especially for the elderly, given the projected increases in both the severity and frequency of atypically warm summers in a future, changed, climate.

Keywords: Ageing Population, Thermal Comfort, Overheating, Temperature Monitoring, Health

6.1 Practical Application

This paper provides new data on the performance of the homes of the elderly in both a typical and atypically warm summer. Our results could be considered for building performance evaluation in homes with elderly occupants to mitigate overheating risk. Crucially, we not only examine the impact of CIBSE criteria on these homes, but also look at thermal acceptance, which is important to understand the true impact of elevated temperatures in this demographic.

6.2 Preamble

This chapter reports the results of two cooling seasons (June – September 2017 and June – September 2018) of temperature monitoring in the 37 participating homes. This chapter represents the fist UK based longitudinal temperature monitoring study to focus on summer temperatures found in homes occupied by older people. This chapter specifically addresses Research Question 3 'During summer periods what internal temperatures are achieved, how comfortable are the participants and how effective are Fanger's PMV/PPD model and the Adaptive model in predicting thermal comfort during summertime?'

Before the study commenced, ethical approval was obtained from the research ethics committee of the Department of Architecture and Civil Engineering at the University of Bath. All participants signed a consent form at the beginning of the first summer phase (July 2017), where they were informed that their data would be confidential and stored in accordance with the Data Act 1998. Furthermore, they were assured that they did not have to answer anything they did not feel comfortable answering and they could withdraw from the study at any point.

6.3 Declaration of Authorship

This declaration concerns the article entitled:									
Summer thermal comfort and health in the elderly.									
Publication status (tick one)									
Draft manuscript		**Submitted**		**In review**		**Accepted**	✓	**Published**	
Publication details (reference)	Accepted (with revisions) in Building Services Engineering Research and Technology Journal								
Candidate's contribution to the paper (detailed, and also given as a percentage).	The author of this thesis has primarily contributed to defining the methodology, conducting the data collection and analysis and writing the manuscript. C Hughes: Formulation of Ideas (80%); Design of Methodology (80%); Data Collection (100%); Data Analysis (80%); Preparation of Manuscript (80%). S. Natarajan: Formulation of Ideas (20%); Design of Methodology (20%); Data Analysis (20%); Preparation of Manuscript (20%).								
Statement from candidate	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.								
Signed						**Date**			

6.4 Introduction

Projections estimate that the global average surface temperature is likely to rise by up to 5.4°C by 2070 (Met-Office 2018). As a result, the frequency, duration and intensity of high external temperatures are likely to increase, and atypically warm summers such as 2003 and 2018 are predicted to become normal by the middle of the century (Hajat et al. 2013). The heatwave of 2003 resulted in 70,000 deaths across Europe (Robine et al. 2008), 2,000 of which were in the UK (Kovats et al. 2006), and the heatwave of 2018 is likely to have caused additional deaths, though estimates are not yet available. Estimates suggest that heat-related mortality could rise by an estimated 257% based on a current baseline of 2000 deaths, if current temperature projections are accurate (Hajat et al. 2013). Consequently, there is increasing concern over the impact of more frequent heatwaves on morbidity and mortality (Basu and Samet 2002, Kenny et al. 2010), particularly in vulnerable groups such as the elderly (Abrahamson et al. 2008).

This is because the elderly are known to be most vulnerable to extreme temperatures, with suggestions that between 82% and 92% of summer mortality occurs in the 65+ demographic (Kenny et al. 2010). Ageing impairs the thermoregulatory system, causing a deterioration in the body's physical response to temperature change, meaning that older people are less able to rapidly cool their bodies during hot weather, leading to morbidity (Astrom et al. 2011, Loughnan et al. 2015). Furthermore, chronic illnesses are more prevalent in older people (Gupta et al. 2017, Loughnan et al. 2015), and those with cardiovascular, respiratory or mobility problems are said to be most at risk of heat related morbidity and mortality (Gasparrini et al. 2011). This can be worsened by medications interacting with personal thermoregulation (Astrom et al. 2011). The 2003 heatwave resulted in the UK Government releasing a heatwave plan (PHE 2018*b*), with the primary aim of reducing summer mortality by providing guidance and specific measures for vulnerable groups. Advice includes staying out of the heat, keeping cool and maintaining a cool environment (PHE 2018*b*). However, despite this, it is suggested that older people do not always recognise their vulnerability (Abrahamson et al. 2008), and consequently do not prepare adequately for heatwaves.

Despite the relatively temperate climate of the UK, much of the current morbidity and mortality is associated with overheating in internal environments (Vardoulakis et al. 2015, Porritt et al. 2012), which is concerning given that older people are believed to spend between 85% and 95% of their time in their homes (Hamza and Gilroy 2011) conducting predominantly sedentary activities (Gupta et al. 2017). Hence, there is a clear need to ensure their homes can be kept at temperate conditions to maintain health. However, the housing of older people is believed to exacerbate health problems (Donald 2009). Despite recognition that housing design is an important factor in reducing heat-related mortality (Loughnan et al. 2015), older people are more likely to be living in sub-optimal houses that are prone to overheating in comparison to younger people (Hamza and Gilroy 2011).

Few studies have investigated the thermal comfort of residential homes during summer periods (Pathan et al. 2017) and none have focused on the elderly despite their increased vulnerability. Much of the current literature uses dynamic thermal modelling (DTM) to focus on overheating of newbuilds or post-retroft (Taylor et al. 2018), low-income households (Vellei et al. 2017, Mavrogianni et al. 2015, 2017), how building fabric influences internal temperatures (Vandentorren et al. 2006), the vulnerabilities in the current housing stock that might lead to future overheating (Lomas and Kane 2013, Beizaee et al. 2013, Mavrogianni et al. 2012), and the influence of occupants on overheating risk (Mavrogianni et al. 2014). Furthermore, some studies recognises that a lack of air conditioning can lead to increased heat-related illness (O'Neill et al. 2005), but this is currently not a significant problem in the UK, as only approximately 3% of homes have air conditioning (Taylor et al. 2016). However, this is predicted to change, with passive ventilation strategies predicted to become inadequate by 2050 (Gupta et al. 2015). Currently, there is no clear link between heat-related morbidity and mortality and socio-economic status (Hajat et al. 2007), however, if air conditioning becomes increasingly necessary then not only will this increase carbon emissions, but it will put pressure on low income households who may not be able to afford sufficient cooling. Older people are known to have lower incomes than that of the working age population, which may create summertime fuel poverty.

Furthermore, the UK population is ageing and by 2050, 25% of the UK population is expected be aged 65 and over, compared to 18% in 2018 (ONS 2017*b*). The greatest population increases are expected to occur in the 80 years and older categories (Wouters 2017). Worryingly, increasing longevity will result in a higher number of older people suffering the morbidity and mortality associated with high temperatures.

Overall, it is likely that there is a strong association between morbidity and mortality in the elderly due to the indoor environmental conditions in their home. However, very little is known about the precise nature of thermal conditions in homes occupied by people aged 65 and over, especially whether they find the internal conditions of their home in summer to be comfortable. This paper sets out to address this gap.

We first briefly introduce the assessment of thermal comfort using the PMV and Adaptive standards, followed by a discussion of current overheating criteria and evidence from other field studies, in Section 6.5. This is followed by Section 6.6 which describes our methods for the field study underpinning the data in this paper. Section 6.7 discusses the results of our field study compared against the PMV/PPD and Adaptive models and the TM52 and TM59 overheating metrics. Finally, Section 6.8 sets our results in context of the current state of the art and points to future work.

6.5 Current standards for summer thermal comfort and health

'Thermal Comfort' is the term used to describe a balance of environmental and personal factors that lead to a person feeling satisfied and comfortable in their thermal environment (Nicol and Roaf 2017). Two key approaches for assessing thermal comfort are the 'PMV-PPD' model (Fanger 1970) and the 'adaptive' model (de Dear and Brager 1998). Methods to calculate the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) are described in ISO 7730 (BSI 2005) and ASHRAE Standard 55 (ASHRAE 2013) and can be used for mechanically ventilated and heated buildings as well as free running buildings. ASHRAE Standard 55 also describes the use of the adaptive model (in free running buildings only), whose European counterpart, with a slightly different formulation, is described in BS EN15251 (BSI 2007*b*).

The differences between these models and their general applicability are well-known in the literature (Vellei et al. 2017), and briefly summarised in Table 1. What is pertinent here is their applicability to the elderly demographic. In terms of model inputs, the personal variables clothing insulation (CLO) and metabolic rate (MET) can be adjusted in PMV suitably to account for differences in clothing or lowered metabolic rates in the elderly, whereas the adaptive model has no specific input adjustments for the elderly. The PMV model and the adaptive models specify different acceptability limits implying narrower temperature bands for vulnerable groups, including the elderly. However, the embodiment of these conditions in the ASHRAE 55 adaptive model (90% acceptability) corresponds to those for typical conditions in BS EN 15251 (Category II), implying the lack of a one-to-one correspondence between the standards. It is noteworthy that both adaptive standards claim applicability for conditions for near sedentary activities where MET $\varepsilon[1,1.3]$, whereas the elderly are known to have a lowered metabolic rate (around 0.9 (Parsons 2002)). Nonetheless, we use the recent CIBSE overheating standard for homes (TM59 (CIBSE 2017)), which is based on the adaptive standard, as it claims general applicability, including for vulnerable occupants such as the elderly.

Table 6.1: Application of current thermal comfort standards to the elderly.

Category	PPD (%)	PMV	t_o **Upper Limit (°C)** ‡	t_o **Lower Limit (°C)** ‡	**Explanation**
I	< 6	$-0.2 < PMV < +0.2$	$0.33t_{rm}+20.8$	$0.33t_{rm}+16.8$	High level of expectation; recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and **elderly persons**.
II*	< 10	$-0.5 < PMV < +0.5$	$0.33t_{rm}+21.8$	$0.33t_{rm}+15.8$	Normal level of expectation and should be used for new buildings and renovations. **Applies to the elderly** as ASHRAE 55 does not provide a separate classification.
III	< 15	$-0.7 < PMV < +0.7$	$0.33t_{rm}+22.8$	$0.33t_{rm}+14.8$	An acceptable, moderate level of expectation and may be used for existing buildings.
IV	> 15	$PMV < -0.7$ or $+0.7 < PMV$			Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.

‡ t_o is the operative temperature
* Category II in EN 15251 (BSI 2007*a*) equates to the general category in ASHRAE 55 (ASHRAE 2013)

6.5.1 Overheating Criteria

CIBSE TM 59 provides the most recent criteria to ensure comfort and prevent overheating (CIBSE 2017), based on one of the three criterions in CIBSE TM52 (CIBSE 2013) and one in CIBSE Guide A (CIBSE 2018). This applies to homes that are predominantly naturally ventilated, a condition met by all the homes in our sample. TM52 criteria are evaluated against ΔT, which is defined as:

$$\Delta T = t_{op} - t_{max} \tag{6.1}$$

Where t_{op} is the hourly indoor operative temperature t_{max} is the upper limit for Categories I or II in Table 1

TM59 uses the first criterion for overheating from TM52, which defines the Hours of Exceedance (H_e), representing the *duration* of overheating:

$$H_e = \Delta T \geq 1^{\circ}C \tag{6.2}$$

The summation is performed over all occupied hours (h) as defined for the type of building. H_e should not exceed 3% of occupied hours for the months May to September inclusive. TM59 refines this criterion for domestic application and adds a separate and additional criterion from CIBSE Guide A for bedrooms as shown in Table 2.

Table 6.2: CIBSE TM59 criteria for assessing overheating risk in free running domestic buildings.

Criterion 1A Living Rooms, kitchens and bedrooms	Criterion 1B Bedrooms only
TM52 Criterion 1 is evaluated with occupied hours set to the range [09.00, 22:00] for living rooms and kitchens and 24 hours for bedrooms.	To guarantee comfort during the sleeping hours the operative temperature in the bedroom between [22:00, 07:00] shall not exceed 26 °C for more than 1%of annual hours.

TM59 notes that homes can fail the remaining two criteria from TM52 and still meet the overheating standard. We describe these for completeness:

Criterion 2 :*Daily Weighted Exceedance (*$\mathrm{W_e}$*)* - deals with the severity of overheating within any one day, which can be as important as its frequency. The We threshold is ≤ 6 per day. Where:

$$\mathrm{W_e} = \Sigma \mathrm{H_e} \cdot \mathrm{WF} \tag{6.3}$$

$$= (\mathrm{h_e}00) + (\mathrm{h_e}1 \cdot 1) + (\mathrm{h_e}2 \cdot 2) + (\mathrm{h_e}3 \cdot 3) \tag{6.4}$$

And:

$$\begin{aligned} \mathrm{WF} &= 0 \text{ if } \Delta\mathrm{T} \leq 0 \\ &= \Sigma \mathrm{H_{ey}} \cdot \Delta\mathrm{T} \text{ if } \Delta\mathrm{T} > 0 \end{aligned} \tag{6.5}$$

where $\mathrm{H_{ey}}$ is the number of hours where $\Delta\mathrm{T} = \mathrm{y}$.

Criterion 3: *Upper limit temperature*: sets an absolute maximum daily temperature

$$\Delta T \leq 4K \tag{6.6}$$

for a room, beyond which the level of overheating is unacceptable.

6.5.2 Field Studies

In the context of this study, it is noteworthy that the above criteria do not discriminate between vulnerable and non-vulnerable occupant groups as very little is known about appropriate threshold temperatures or acceptable durations of overheating in vulnerable populations such as the elderly. This is because, surprisingly little is known about the achieved internal temperatures in such homes and their acceptability to the occupants. This is particularly important given that a disproportionate rate of morbidity and mortality occurs in the elderly demographic. There are very few domestic summer temperature monitoring studies, as most focus on winter temperatures where the associated mortality tends to be an order of magnitude greater than summer mortality. However, as global temperature increases, the instances of summer mortality are likely to increase and consequently the importance of understanding the internal environment of those most at risk, including the elderly, will become more significant. To date there have been a small number of UK temperature monitoring studies, of varying sample sizes, as summarised in Table 6.3.

Table 6.3: Chronological summary of domestic summertime temperature monitoring studies in the UK.

Study	**Period**	**Sample size**	**Coverage**	**Sensor Type**	f	**Overheating Metric**	$\bar{t}_{LR}$ **(°C)***	$\bar{t}_{BR}$ **(°C)***	**SES**	**Include Elderly**
Summerfield (Summerfield et al. 2007)	Feb '05 July '06	15	Milton Keynes	HOBO U12-012	10-30		19.8	19.3	No	
Beizaee (Beizaee et al. 2013)	July '07 March '08	207	England	HOBO UA001-08	45	Guide A BS EN 15251	21.8	21.6	Yes	
Oraiopoulos (Oraiopoulos et al. 2015)	Summer '09	230	Leicester	HOBO Pendant	60		22.2	22.4	No	Yes
Lomas (Lomas and Kane 2013)	July '09 March '10	248	Leicester	HOBO UA001-08	60		16.4		Yes	Yes
Pathan (Pathan et al. 2017)	Summer '09 Summer '10	122	London	HOBO U12-012	10	ASHRAE 55				
EFUS (Symonds et al. 2017)	Summer '11	823	England	TinyTag Transit			Yes	Yes		
Sameni (Sameni et al. 2015)	Summer '11 '12, '13	25	Coventry		60	TM 52	25†		No	
Gupta and Kapsali (Gupta and Kapsali 2016)	Jan-Dec '13	6	SE England		5	Guide A TM52	21-24		Yes	
Jones (Jones et al. 2016)	Summer '13	3	SW England	HWM Ecosense	5	Guide A BS EN15251	24	24	No	
Baborska-Narozny (Baborska-Narozny et al. 2015)	April '13 April '14	20	Leeds	iButton	30	Guide A	23.45		Yes	
Vellei (Vellei et al. 2016)	Summer '14	46	Exeter, UK		5 mins	TM 52	23.9		Yes	No

Notes:
f is sampling frequency in minutes
* LR is living room and BR is bedroom
t is mean temperature
† estimated from graph
SES whether a thermal comfort or other socio-economic survey was undertaken

6.5.3 Research Questions

The literature review suggests that there is inadequate evidence on the effect of the indoor thermal environment on the elderly. Little is known about what temperatures are achieved, whether or not the occupants are comfortable at the achieved temperatures and what effect this has on health. This is especially concerning given that this demographic is most at risk and increasing most rapidly in comparison to other age classes in the population. Consequently, this paper addresses three key questions:

1. Do the temperatures achieved in the homes of the elderly meet the PMV-PPD, Adaptive and TM59 standards for a typical summer and an atypically warm summer?
2. Are the temperatures achieved in the homes of the elderly considered comfortable by the occupants?

6.6 Methodology

This section describes the longitudinal temperature monitoring study designed to address the above research questions. The study was conducted in the city of Bath, South-West UK, with participants living within a three mile radius of the city. Given the increased vulnerability of older people to extreme heat, the only requirement for participation was to be aged 65 or over. A total of 43 homes with 59 occupants were recruited. Of these, 37 homes were used for analysis in the first summer, and 16 homes in the second summer [1]. Each home designated one person to respond to the surveys, which were disseminated monthly, to ensure continuity. The mean age

[1] The reduction in participating homes is due, in part, to a natural drop in participant retention (as these homes were also part of a winter field study, reported elsewhere), sensor failures and relocation, declining health or death.

of our sample is 76.3 years (n = 59, s = 9.1 years).

6.6.1 Sensors

Two sensors were placed in each home:

- living room sensor
- bedroom sensor

The living room sensor measures both temperature and humidity and the other two sensors measure temperature [2]. Sensors that measure both temperature and humidity are considerably more expensive than temperature sensors, so this was judged the optimal combination to enable humidity to be recorded for the PMV calculations whilst sufficiently equipping each of the participating homes. Sampling frequency was set to 90 minutes (i.e. 16 readings/day) due to the total memory capacity of the sensors. CIBSE TM59 criteria use operative temperature (T_{op}) which depends on both air temperature (T_a) and mean radiant temperature (T_m), whereas our sensors only measure T_a. Tm can be affected by both high radiant temperatures and elevated air velocity as these alter the radiant and convective exchanges for the standard black globe thermometer usually used to undertake measurements. We assessed the likely impact of these through a transverse survey in November 2016 using the ISO 7730 compliant Swema equipment, covering the 30 homes that had joined our study by that date. A regression of T_a and T_m showed a strong correlation (R2 = 0.96), suggesting that T_a is a good proxy for T_m. Measurements of air velocity taken at the same time indicated that all but three homes had $V_a < 0.1ms^{-1}$, with $V_{amax} < 0.15$ ms^{-1}. These results are supported by the literature suggesting that, in practice, the difference between T_a and T_m tend to be small (Walikewitz et al. 2015, Nicol et al. 2012) and hence T_a can be taken as a good approximation of T_{op}.

[2] Only 6 living rooms in 2018 were fitted with temperature + relative humidity sensors, the remaining being temperature only.

Nonetheless, as this paper reports summer conditions when greater variations in T_m and V_a could be expected, our results should be read in context of the assumption that $T_{op} = T_a$.

6.6.2 Surveys

The survey had the following key features:

- The survey was designed to assess both thermal comfort and health. The thermal comfort survey was based on a reduced set of the standard survey design contained in ASHRAE 55 and commonly used in other studies (Critchley et al. 2007, BSI 2007*a*, ASHRAE 2013), including information necessary for PMV-PPD calculations such as CLO values. Health metrics were adopted from the NHS Health Survey for England (Service 2016), the Short Form-36 Questionnaire (RAND 1980) and the 'Older People's Quality of Life Questionnaire' (Bowling 2013).
- Although no time was set for answering the questions, the surveys were almost exclusively answered in the daytime and hence reflect daytime comfort.

6.6.3 Summer Weather

Surveys and monitoring occurred over the summers (June - September) of 2017 and 2018. Figure 6.1 shows the mean summer temperatures recorded between 2001 and 2018 for the UK and South-West England, where the temperature monitoring took place. The average temperature across all years is 14.7°C (s = 0.61°C) for the UK and 15.4 °C (s = 0.66°C) for the South-West, with 2003, 2006 and 2018 being atypically warm (i.e. at least 1 standard deviation greater than the mean). In Bath (where monitoring took place) summer 2017 averaged 15.5°C and summer 2018 averaged 17.1°C. Hence, the summer of 2017 is representative of a typical summer whilst that of 2018, an atypically warm summer, further evidenced in Figure 2.

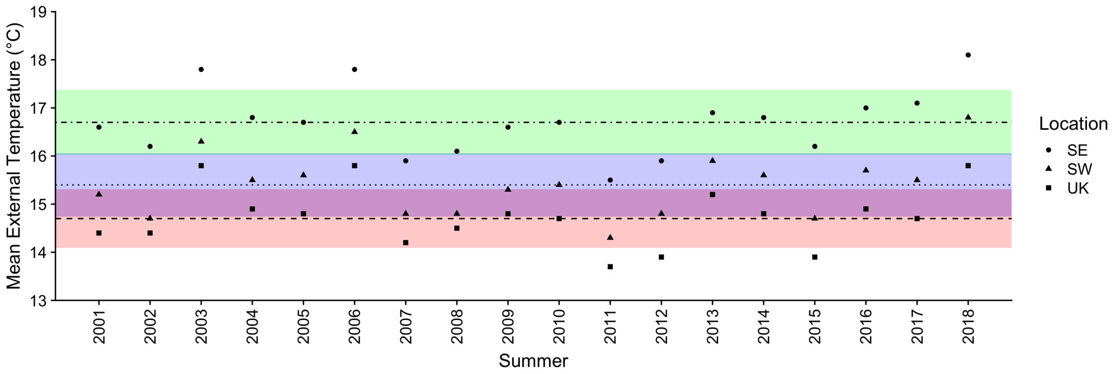


Figure 6.1: UK, South East and South West England summer mean external temperatures between 2001 and 2018. Horizontal lines and colours indicate UK (dashed, red), SE (dot-dashed, green) and SW (dotted, blue) means and standard deviations. The purple area is the overlap between UK and SW standard deviations. Note that in the South West, 2017 was representative of an average summer whereas 2018 was well outside one standard deviation. Data source: [(Office 2018)]

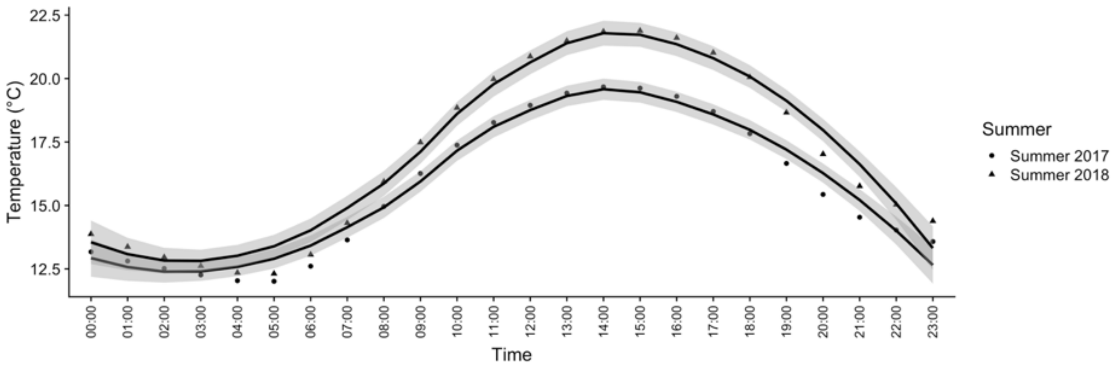
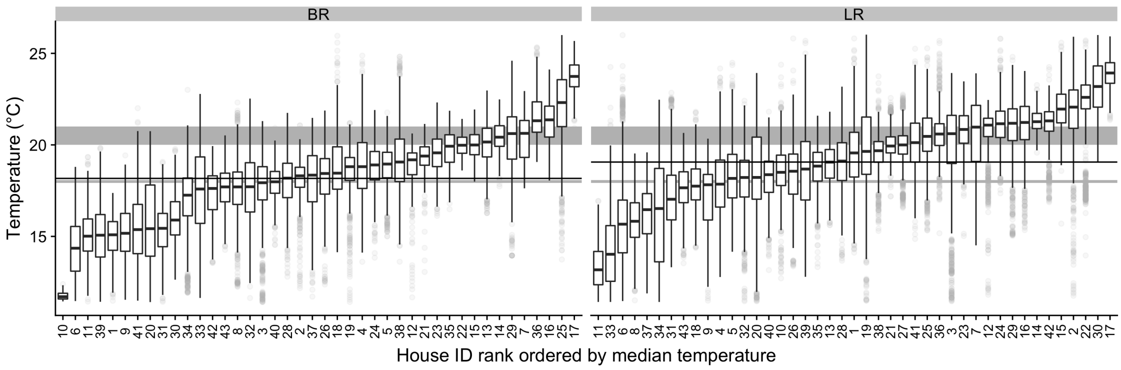


Figure 6.2: Hourly mean temperature for summer 2017 and 2018, with 95% confidence interval (grey band).

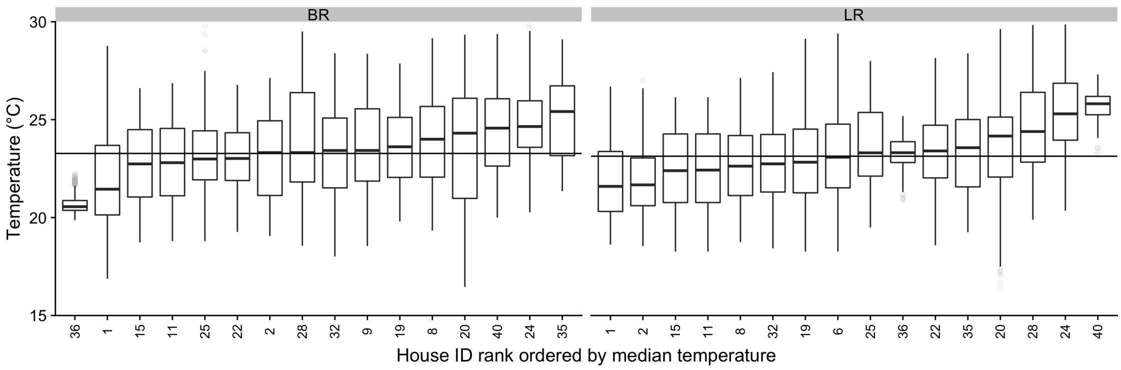
External weather data for Bath was obtained from two sources: the Copernicus Atmosphere Monitoring Service (CAMS) (Schroedter-Homscheidt 2017) and the Modern-Era retrospective analysis for Research and Applications (MERRA) (Gelaro 2017). Data was sourced for the entire duration of the study (June – September 2017 and June – September 2018) at hourly intervals.

6.7 Results

Box-plots for hourly internal living room and bedroom temperatures for each home across the two summers (2017 and 2018) are shown in Figure 6.3. For summer 2017 the mean internal living room temperature was 21.2°C (s = 1.2°C) and the mean internal bedroom temperature was 21.2°C (s = 0.9°C) and for summer 2018 the mean internal living room temperature was 23.0°C (s = 1.1°C) and the mean internal bedroom temperature was 23.3°C (s = 1.0°C). A Pearson's Product Moment Correlation Coefficient of the two summers shows a weak positive correlation suggesting that the internal temperatures did differ significantly between the two ($r = 0.33$ for living rooms and $r = 0.34$ for bedrooms, $p < 0.05$ for both). Expectedly, the atypically warm summer shows a mean increase in internal temperature of 1.97°C, compared to the typical summer.



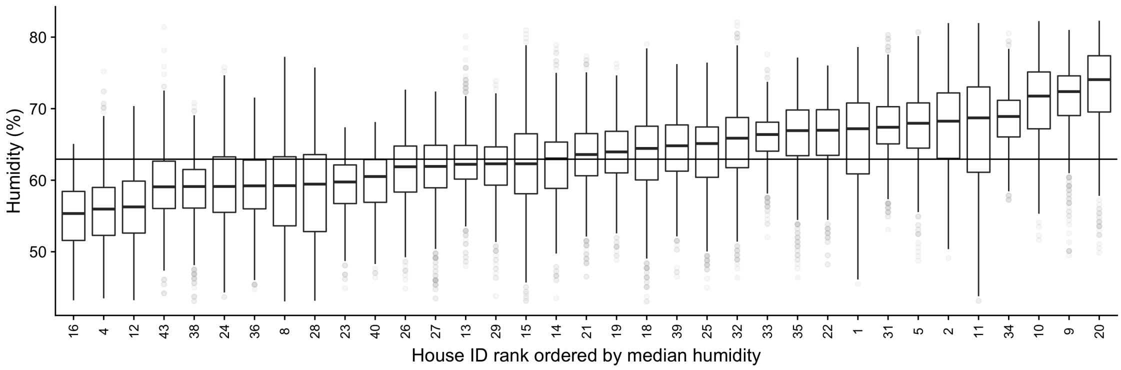
(a)



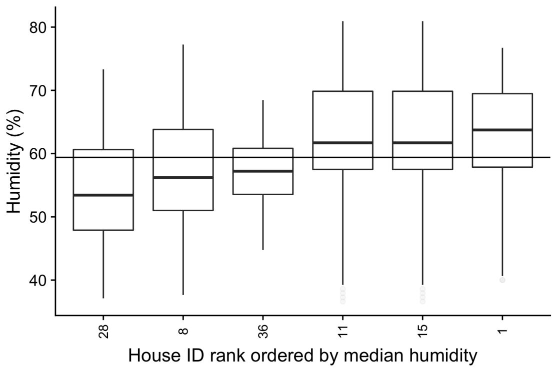
(b)

Figure 6.3: Ranked median summer internal bedroom (BR) and living room (LR) temperatures for each house across 2017 (a, n=37) and 2018 (b, n=16). The black lines show group means for each room.

Box plots for the internal humidity measured using the living room sensor, for each home across the summers of 2017 and 2018 are shown in Figure 6.4. The mean relative humidity across both summers was 62.1% (s = 8.3%).



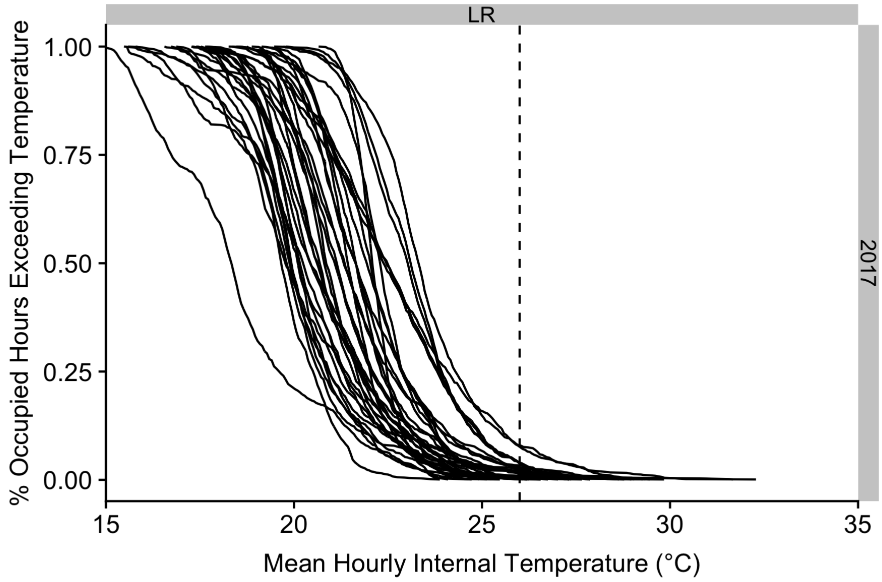
(a)



(b)

Figure 6.4: Ranked median internal humidity across both summers ((a) = 2017, (b) = 2018), with black line representing the mean.

As overheating is influenced by maximum temperatures, Figures 6.5 and 6.5 show the percentage of occupied hours exceeding a range of internal temperatures for each dwelling split by room and year.



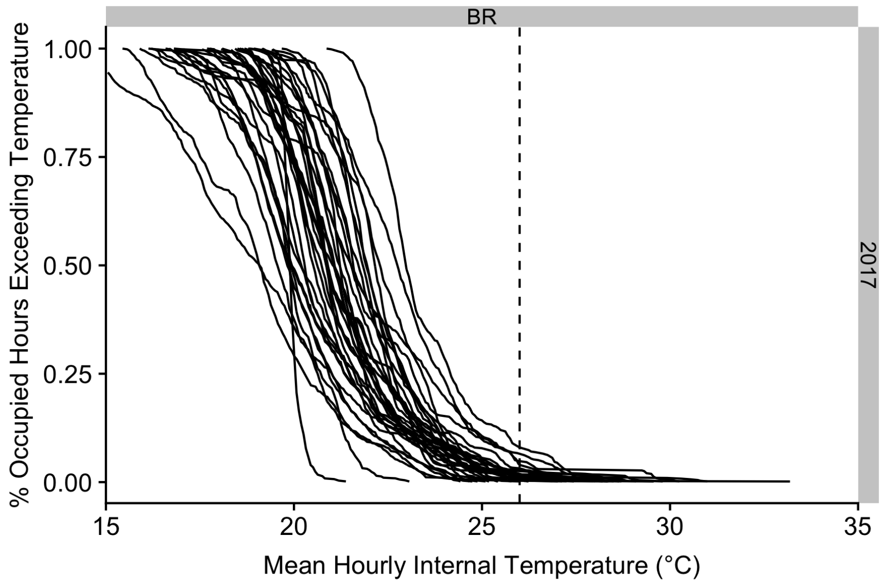


Figure 6.5: Percentage of occupied hours (calculated according to TM59 criteria) exceeding a range of internal temperatures by room type and year. Living Room (LR) are in the top row and bedroom (BR) in the bottom row for 2017. All graphs marked with 26°C threshold (dashed line) per TM59 guidance for bedrooms and PHE's Heatwave Plan for care homes (applied to Living Rooms in our data set). Note that the home with the identifiably different profile (e.g. in the 2018-BR plot) is a basement flat with high thermal mass and low solar gains.

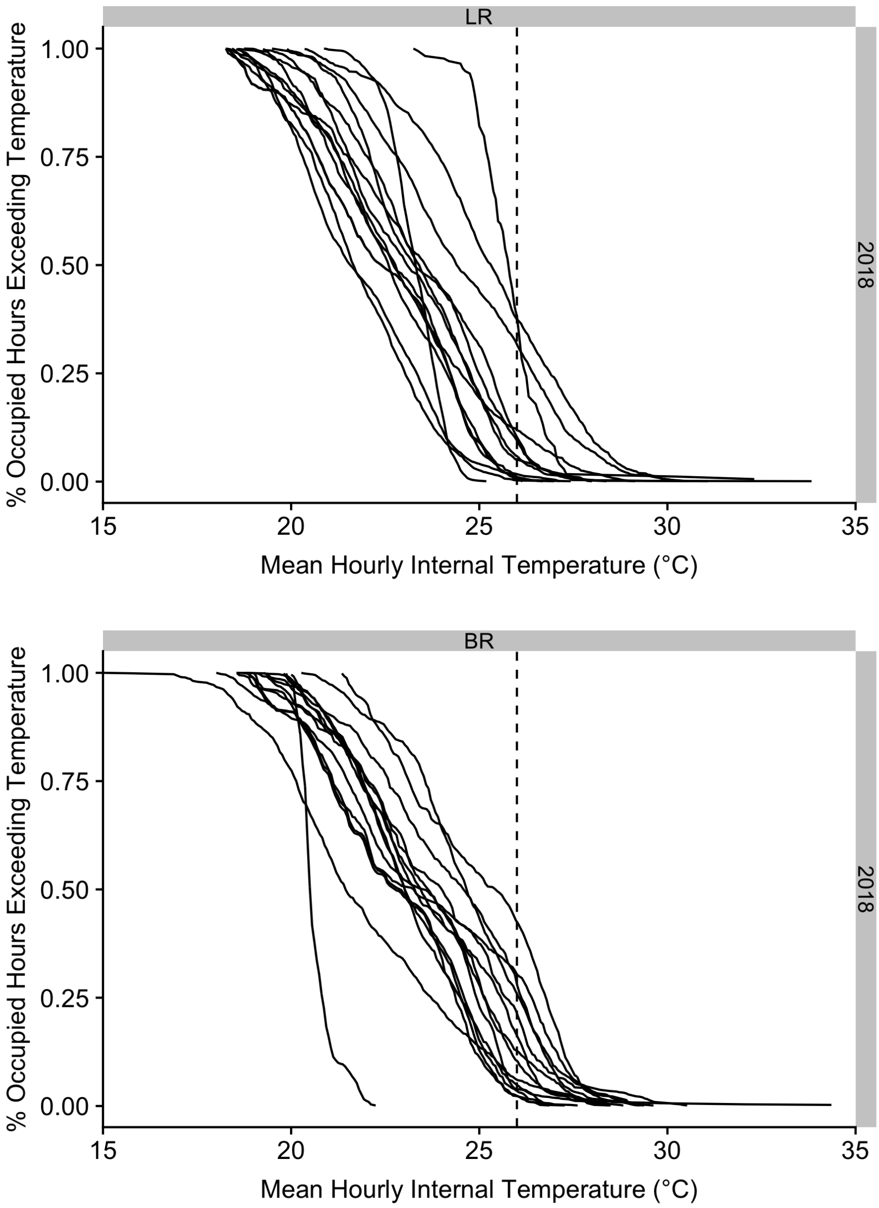


Figure 6.6: Percentage of occupied hours (calculated according to TM59 criteria) exceeding a range of internal temperatures by room type and year. Living Room (LR) are in the top row and bedroom (BR) in the bottom row for 2018. All graphs marked with 26°C threshold (dashed line) per TM59 guidance for bedrooms and PHE's Heatwave Plan for care homes (applied to Living Rooms in our data set). Note that the home with the identifiably different profile (e.g. in the 2018-BR plot) is a basement flat with high thermal mass and low solar gains.

We observe that, as expected, more homes have longer durations of overheating in the atypically warm summer compared to the typical summer. For living rooms, although there is no specific guidance on internal temperatures for homes, sources such as Public Health England's Heatwave Plan (PHE 2018*b*) suggest that internal areas in care homes (known to be occupied by a similar demographic to our sample) should be kept below 26°C, hence, we use this as a guideline. In the typical summer of 2017 we observed that of the homes exceeding the 26°C limit, they did so for a maximum of 10% of occupied hours, whereas for 2018 this rose to 38% of occupied hours. For bedrooms, homes shown to exceed the 26°C limit did so for a maximum of 8% of occupied hours in the typical summer of 2017, however, this increased to a maximum of 42% of occupied hours in the atypically warm summer of 2018. This is concerning given that occupants were exposed to significantly longer periods of overheating in the atypically warm summer, especially in bedrooms where they are less able to adapt their environment when sleeping.

6.7.1 Thermal Comfort

In the surveys, participants responded with their Thermal Sensation Vote (TSV), which measures how comfortable they felt in their home, using the widely used Bedford Thermal Comfort scale (Table 6.4).

Table 6.4: Bedford Thermal Comfort Scale.

Response	Scale
Much too warm	3
Too warm	2
Comfortably warm	1
Neither warm nor cool	0
Comfortably cool	-1
Too cool	-2
Much too cool	-3

The following sections compare TSV data against both PMV-PPD and Adaptive model predictions.

6.7.1.1 PMV-PPD Approach

Figures 6.7 and 6.8 show normalised density plots for the self-reported TSV and the model predicted PMV. Taking TSV ε[-1, 1] as comfortable, we get 91% of votes for summer 2017 and 89% for 2018 falling in this category [3]. Mean PMV_{2017} was -1.2 whereas mean TSV_{2017} was +0.1; and mean PMV_{2018} was -0.5 whereas mean TSV_{2018} was +0.3.

[3] Although Categories I and II of the standards specify votes in the range [-0.2,+0.2] and [-0.5,+0.5] respectively as comfortable, our surveys are on an ordinal scale. The effect of taking comfort to be between [-1,+1] is mitigated through the observation that the majority of votes in both summers were neutral (i.e. 0): 42% for 2017 and 52% for 2018. This minimises the risk of biasing the comfort band in either direction.

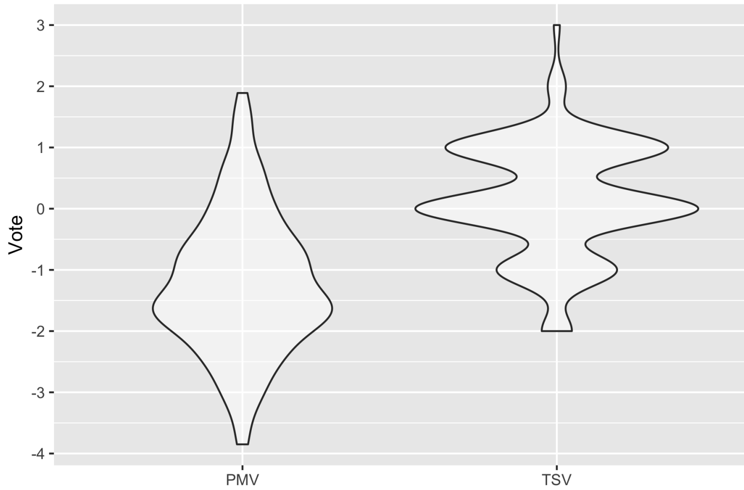


Figure 6.7: Density plots for TSV and PMV in summer 2017.

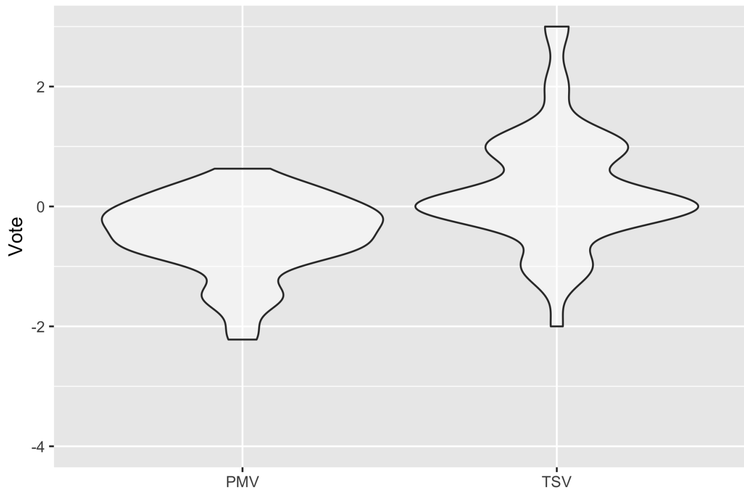


Figure 6.8: Density plots for TSV and PMV in summer 2018.

From this, two inferences are drawn: (i) occupants were broadly comfortable in both the typical and the atypically warm summer, suggesting adaptation is in play and (ii) PMV tends to predict colder sensations than observed. Poor Spearman's rank correlations between PMV and TSV for both summers (ρ= -0.06 for 2017 and ρ= 0.25 for 2018), supports the latter conclusion.

6.7.1.2 Adaptive Approach

Figures 6.9 and 6.9 show the results of applying the BS EN ISO 15251 adaptive model to our data. For the typical summer 2017, 30% of living room hours and 29% of bedroom hours were within Category I, which is considered acceptable for vulnerable occupants including the elderly, and 54% of living room hours and 55% of bedroom hours were within the Category II parameters. It is noteworthy that the majority of the remaining conditions are below, not above, the thresholds. For the atypically warm summer of 2018, 69% of living room hours and 66% of bedroom hours were within the adaptive Category I parameters and 86% of living room hours and 84% of bedroom hours were within the Category II parameters. This apparent “increase” in comfortable hours is due to the fact that the adaptive model thresholds are valid from 15°C trm (vertical line in the graphs), and that a significant proportion (27.6%) of 2017 hours were below this cut off.

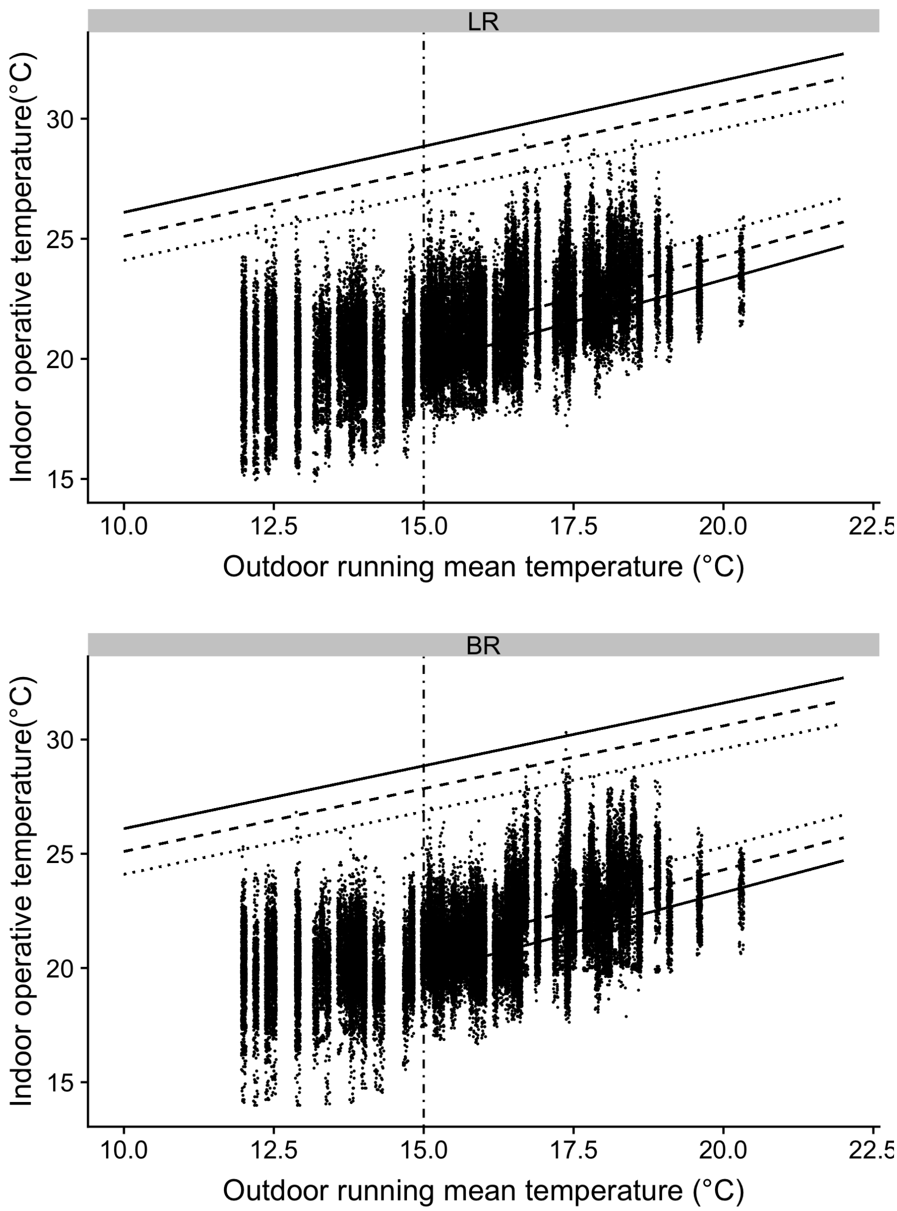


Figure 6.9: Outdoor running mean temperatures (°C) and indoor operative temperature (°C) for all participating homes in summer 2017, split by room type (LR = living room, BR = bedroom), with the ISO 15251 Category I (dotted), II (dashed) and III (solid) limits. The vertical dot-dash line represents the minimum temperature for which the adaptive model claims validity.

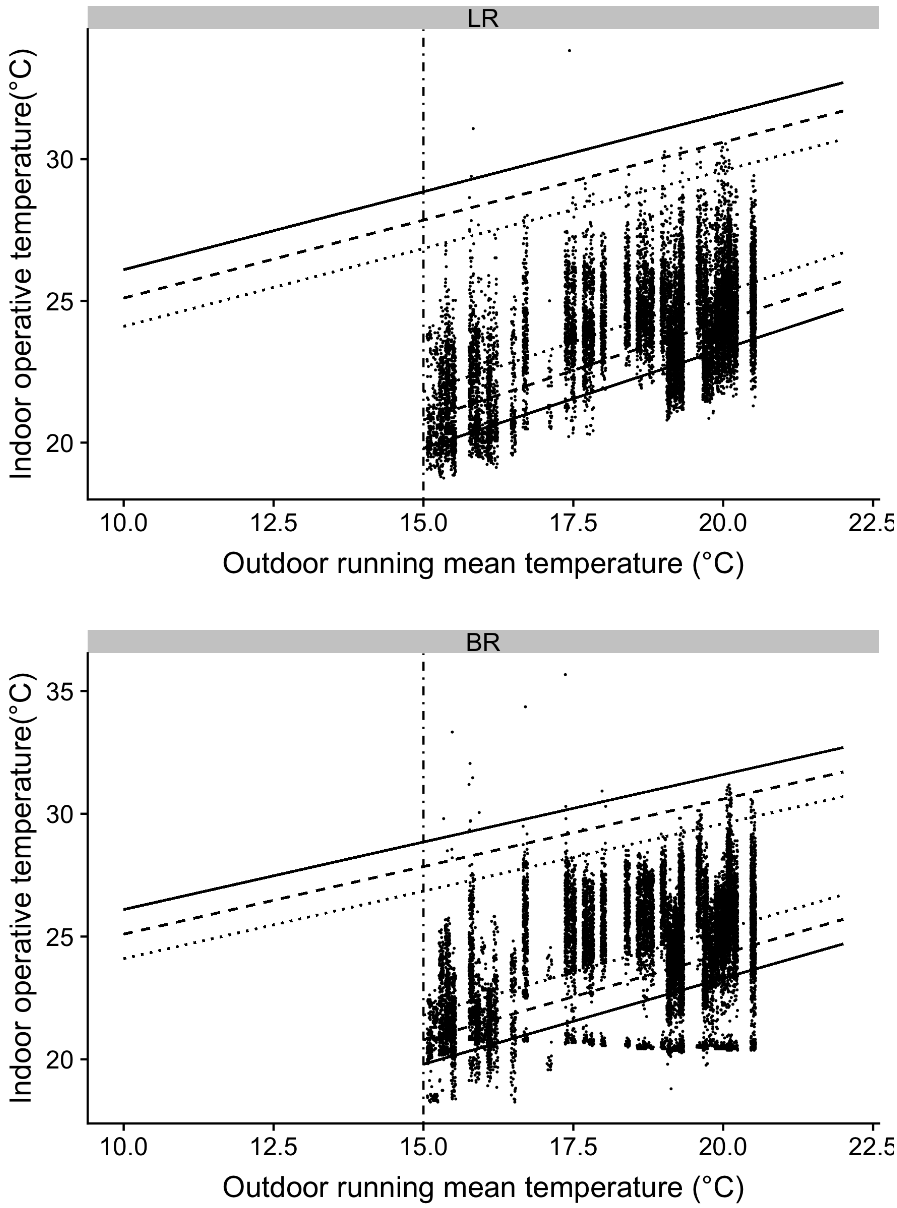


Figure 6.10: Outdoor running mean temperatures (°C) and indoor operative temperature (°C) for all participating homes in summer 2018, split by room type (LR = living room, BR = bedroom), with the ISO 15251 Category I (dotted), II (dashed) and III (solid) limits. The vertical dot-dash line represents the minimum temperature for which the adaptive model claims validity.

Figures 6.11 and 6.12 plots TSV against the adaptive thresholds using a total of 114 votes (from 35/37 homes) returned in 2017 and 48 votes (from 16/16 homes) in 2018. For 2017, of the 91% self-reported responses within TSV ε[-1,+1], 28.6% were within the Category I temperature limits and 56.1% within Category II limits. In summer 2018, of the 89% self-reported responses within TSV ε[-1,+1], 53.5% were within the Category I limits and 72.9% within Category II. Again, we observe that TSV maps poorly to the thresholds set by EN 15251 with occupants in our sample finding a wider range of indoor temperatures comfortable, particularly those below the thresholds.

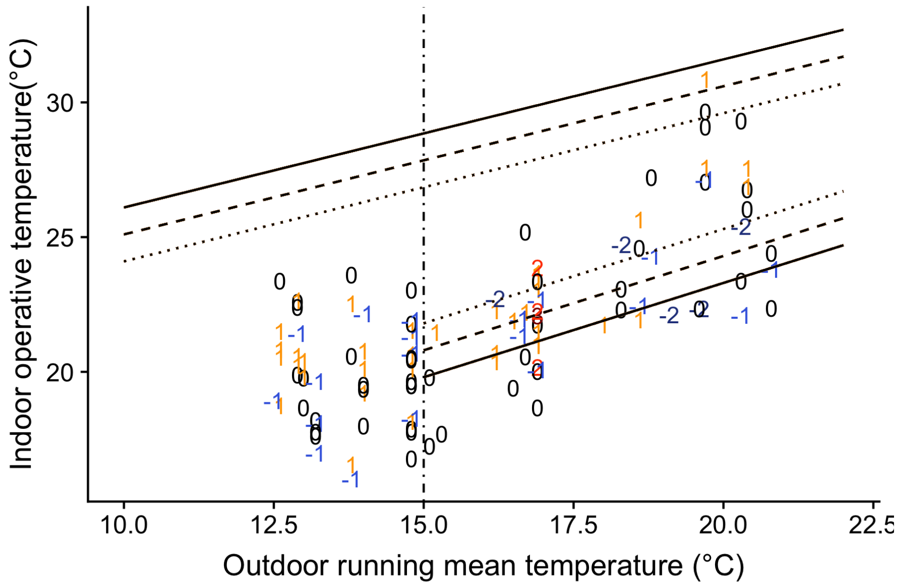


Figure 6.11: TSV for summer 2017 (N = 114) with the ISO 15251 Category I (dotted), II (dashed) and III (solid) limits. Coloured numbers represent TSV vote ranging from +3 (deep red), through 0 (black) to -3 (deep blue). The vertical dot-dash line represents the minimum temperature for which the adaptive model claims validity.

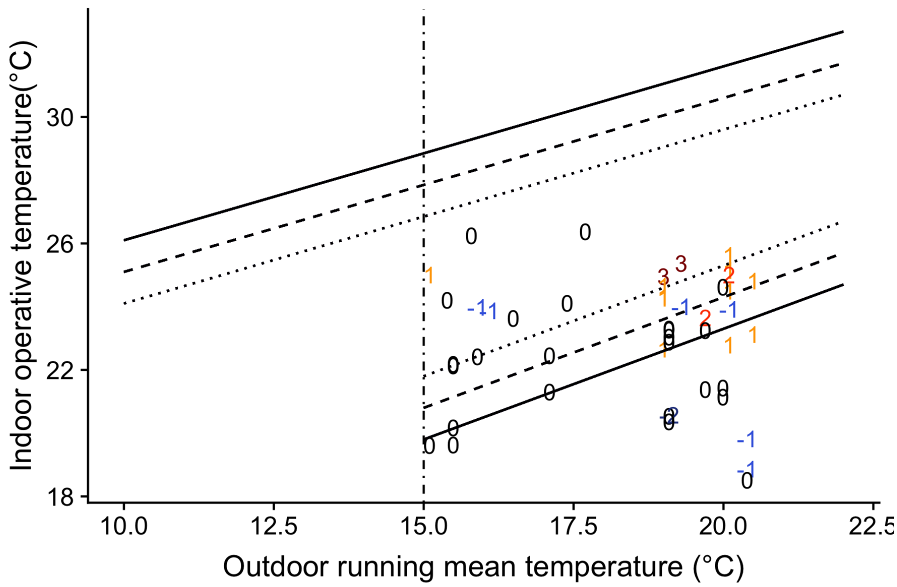


Figure 6.12: TSV for summer 2018 (N = 48) with the ISO 15251 Category I (dotted), II (dashed) and III (solid) limits. Coloured numbers represent TSV vote ranging from +3 (deep red), through 0 (black) to -3 (deep blue). The vertical dot-dash line represents the minimum temperature for which the adaptive model claims validity.

6.7.1.3 TM59 Criteria

In order for a home to meet TM59 criteria, it must meet TM52 Criterion 1 for all rooms and the following CIBSE Guide A criterion for bedrooms only.

Figure 6.13 shows how each home performed against Criterion 1A, in each summer. Only one of the participating homes failed Criterion 1A in summer 2017, whereas 8 homes (50%) failed in summer 2018. Note that we observe failures in either the bedroom (House IDs 20, 24, 25, 28) or the living room (House IDs 1, 6, 19, 33) but never both.

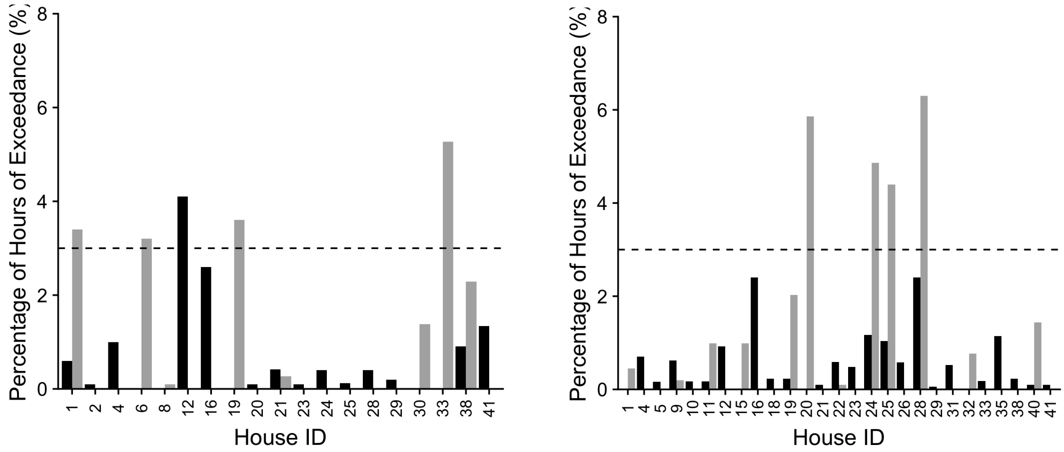


Figure 6.13: TM59 Criterion 1A: Percentage of hours of exceedance per home for 2017 (black) and 2018 (grey) in the living room (left) and bedroom (right), with 3% threshold (dotted line).

Figure 6.14 shows TM59 Criterion 1B for bedrooms. In summer 2017, 21 homes (57%) exceeded 26°C for over 1% of time and therefore failed the criterion, whereas for 2018, 15 homes (94%) failed the criterion. Mean percent hours of exceedance in 2017 were 1.8% above 26°C whereas this increased to 6.6% in 2018.

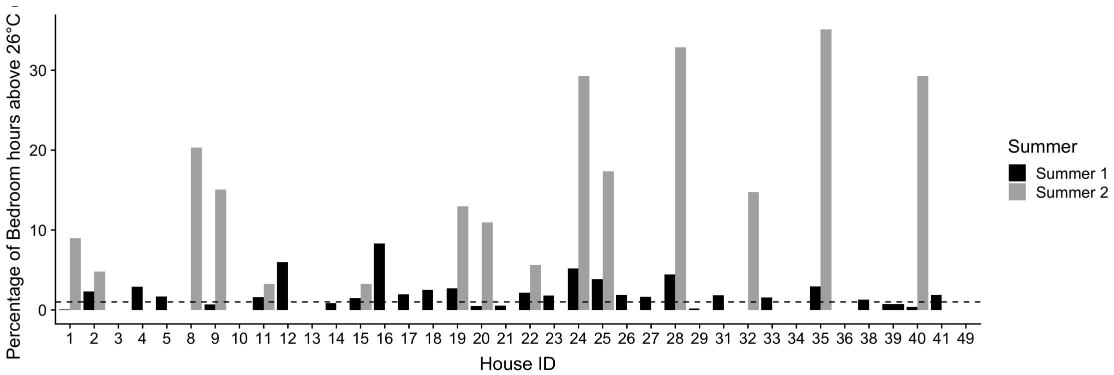


Figure 6.14: TM59 Criterion 1B: Percentage of bedroom hours above 26°C per home for both summers, with 1% threshold (dotted line).

Overall, in the typical summer of 2017 only one home failed both TM59 criteria (2.7%) whereas in the atypically warm summer of 2018, 5 homes failed both criteria (31.3%). This suggests that the choice of either criterion failing being sufficient to fail the standard as a whole is correct in order to minimise overall risk. All homes that failed Criterion 1A also failed Criterion 1B, suggesting that the latter standard may be sufficient to identify overheating on its own.

6.7.1.4 TM52 Criteria

Here we analyse compliance against criteria 2 and 3 of TM52. Though the TM59 standard does not mandate such compliance, we include them for completeness and to assess whether other risks, particularly those emanating from severity of overheating are evident in our data. Criterion 2 measures the severity of overheating using the daily weighted exceedance, which should not exceed 6 in any one day. Figure 6.15 shows, for each home, the number of days when the daily weighted exceedance > 6 in each summer. The failure rate for 2017 was 24% and 50% for 2018.

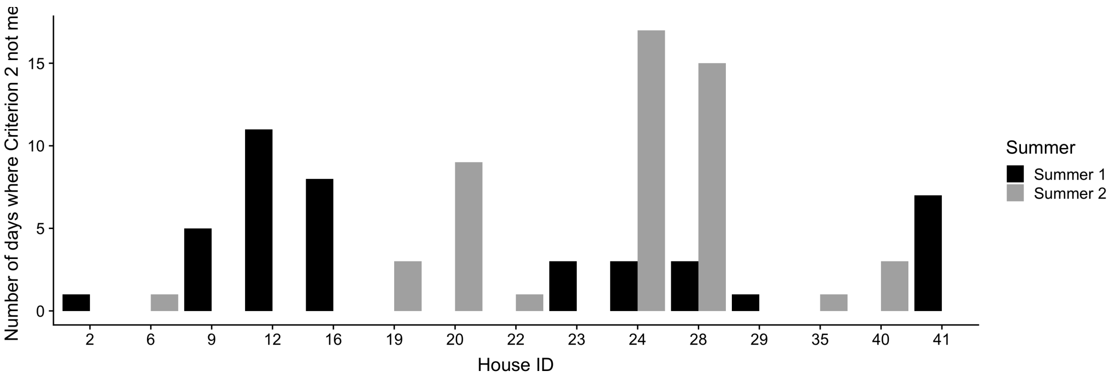


Figure 6.15: Number of days for each home where the daily weighted exceedance (Criterion 2) was not met.

Figure 6.16 shows that the upper limit temperature (Criterion 3) was exceeded in 14% of homes in 2017 and 31% in 2018. Analysis at the dwelling level suggests that all homes failing TM52 Criterion 2 also failed both TM59 Criteria. Only one home failing TM52 Criterion 3 failed to be identified in either TM59 criterion (House ID 6), and indeed was not identified by TM52 Criterion 2 either. However, the fact that this home fails Criterion 3 on only 1 day, suggests that TM59 correctly leaves out Criteria 2 and 3 from TM52.

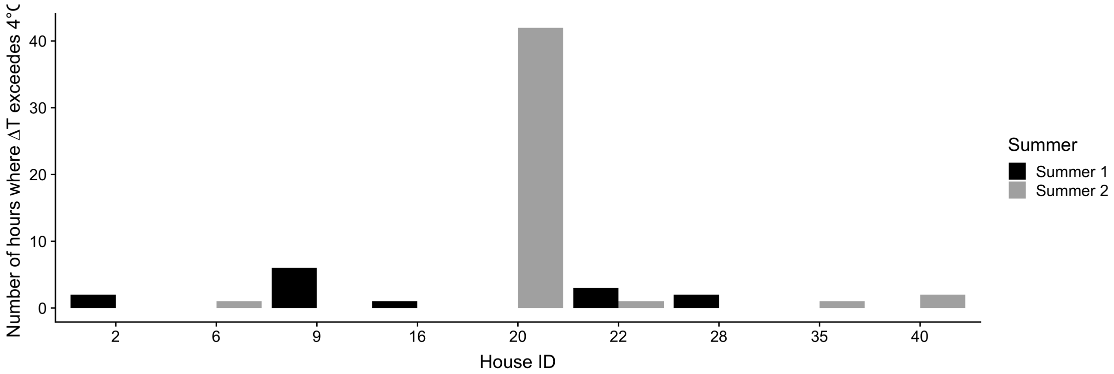


Figure 6.16: Number of hours per home where the change in temperature was above 4°C.

6.8 Discussion and Conclusion

This paper has presented new data and analysis focusing, for the first time, on the summertime performance in the homes of the elderly located in the South West of the UK covering both a typical and an atypically warm summer.

With respect to thermal comfort, our results demonstrate that the PMV/PPD index is poor at capturing true comfort in both summers. For 2017 the PMV results suggested most people should have been feeling cold (with the majority of PMV outputs between [-1, -2]), whereas the TSV suggested that people felt comfortable, with 91% of votes between [- 1, +1]. Although the strength of the correlation between PMV/PPD predictions and TSV for summer 2018 is slightly better than for summer 2017, PMV still suggests people would be feeling slightly cool with the majority in the range -1 to 0. This discrepancy between PMV and TSV is perhaps not surprising given that these homes are naturally ventilated, to which environment the PMV model is known to be less suited.

What is more surprising is the disconnect between the adaptive model and TSV data. Given that an average of 90% of the votes across both summers were within [-

1,+1] the fit of these votes to the adaptive model was, at best, 73%. Fit to Category 1, designed for vulnerable groups such as the elderly, was particularly poor with a maximum of 54% and falling as low as 29%. This discrepancy is harder to explain, but one key source of the problem could be the fact that homes form a very small fraction of the data used to derive the adaptive model. Since overheating affects people differently during waking and sleeping hours, CIBSE TM59 defines separate tests for living rooms (Criterion 1A) and bedrooms (Criterion 1B). In our sample, only one home failed Criterion 1A in the typical summer of 2017 (3%) rising to eight in the atypically warm summer of 2018 (50%), showing a significant increase in overheating risk in the latter year.

However, the fact that 94% of bedrooms failed TM59 Criterion 1B in the atypically warm summer of 2018, i.e., had more than 1% of night-time hours at temperatures 26°C and above, is more worrying. Given that this was already at 57% in the typical summer of 2017 demonstrates that the problem may be more pervasive. Since failure in either criterion results in overall failure (i.e. for the entire dwelling) under TM59, the overall failure rates were also 57% and 94% in 2017 and 2018, respectively. Furthermore, these high failure rates for Criterion 1B subsume failures in 1A and the remaining two criteria in CIBSE TM52, suggesting that this metric alone may be sufficient to identify overheating risk, if it were deemed fit for purpose. However, given that our surveys were answered in the daytime and hence are not necessarily representative of thermal comfort during nigh time, a greater study of acceptable night time temperatures and their effect on quality and quantity of sleep is needed, given our results for the other rooms.

Based on the results of this study there seems to be a disconnect between existing models of comfort and the true experience of elderly. This is worrying, especially in the case of the adaptive model which is designed for use in naturally ventilated buildings. Since the entire edifice of overheating analysis now relies on the adaptive model being true, its failure in capturing comfort – especially for the elderly – could have significant consequences on how we respond to the threat of increasing temperature as the climate changes. It is clear that further studies are necessary investigating the suitability of adaptive comfort in domestic settings for both day and night time, with specific relation to vulnerable occupants, such as the elderly.

6.9 Acknowledgements

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6.10 Postscript

The results reported in this chapter show that both Fanger's PMV/PPD model and the adaptive model do not accurately predict thermal comfort. In fact, people felt warmer than the PMV/PPD model suggested. Results also show a clear difference between the adaptive model outputs and TSV, which is concerning for not only health but especially as this forms the basis of the TM59 criteria. That instances of overheating were more prevalent in the atypically warm, compared to typical, summer was expected, however, the insufficient fit of the adaptive model raises questions over the suitability of the TM59 metric, especially as attention increasingly focuses on the threat of climate change.

Chapter 7

Discussion

This thesis, through conducting a longitudinal temperature monitoring study over two winters and two summers, has presented new data and findings on thermal comfort of people aged 65 and over in the UK.

By monitoring 43 homes in Bath, UK for two heating seasons, data necessary for investigation into Research Question 1 was collected, and reported in Chapter 4. This RQ was designed to identify what temperatures were achieved during winter periods in homes occupied by older people, how comfortable they were and to enable a better understanding of the applicability of Fanger's PMV/PPD model to this demographic. The findings have shown that recommended temperatures are only partially achieved by older people, with only 30% of participants achieving the 20-21°C suggested for older people and 40% achieving between the baseline temperature of 18°C and 21 °C, meaning that, concerningly, 30% of participants were found to be under heating their homes and 70% were not achieving the elevated temperature for the elderly. Hence, this supports the literature in raising concerns over the health implications of under heating for the older demographic (Chard and Walker 2016, Donald 2009). Surprisingly, however, self reported comfort votes indicated that participants felt comfortable at lower than recommended temperatures, with 79% of TSV votes in the [-1,+1] category. Interestingly, much literature discusses the sacrifices older people make in achieving thermal comfort when occupying cold homes (Day and Hitchings 2011, O'Neill et al. 2006*a*). Given how this study has shown that over two thirds of participants were not achieving the elevated temperature for the elderly, yet 79% reported comfort, this suggests a clear disconnect between recommendations and the lived experience of the participants. Perhaps this is because recommended internal temperatures are not reflective of older people, which is possible given the recommendations are approaching 40 years old (Ormandy and Ezratty 2012). However, this also might suggest that heating habits and familiarity play a significant role in thermal comfort of older people, as is suggested within the literature (Wright 2004). It is also important to recognise some studies have concluded that thermal perception decreases with age (Blatteis 2012), which could indicate that the participants are not wholly able to accurately report their level of comfort. However, this is known to be influenced by such a variety of factors, including gender, time of day, season and lifestyle of participant (Blatteis 2012), that it cannot be considered truly reflective of all older people. Additionally, there was no clear link found between low internal temperatures and instances of morbidity and mortality in the sample, although given the severity of EWDs and the strength of the literature around this topic (Crawford et al. 2003, Donald 2009, Guy et al. 2015, Day and Hitchings 2011) it is clear that further investigation is necessary. Equally, it is important to recognise that as the participants in this study were in relatively good health, it is unlikely that especially high instances of morbidity and mortality would have occurred.

Self reported comfort was found to be at least 1 vote higher than the PMV/PPD model predictions, suggesting the model over predicts true comfort and hence is not suited to predicting thermal comfort in the 65+ demographic. Much literature has questioned the use of the PMV/PPD model, especially in relation to its calculation of the environmental variables (Havenith 2001, Humphreys and Nicol 2002, Nicol and Roaf 2017). The findings of this study further support these criticisms. As a result a mixed effects linear regression model (PMVe) was proposed in Chapter 4, which reduces RMSE error by 40%. Modelling a subset of 6 of the participating homes enabled comparison between the classical PMV/PPD model and the PMVe model which reduced predicted energy demand by 44%. This suggests the PMVe model may be better suited to predicting thermal comfort in older people, although further investigation is necessary. Findings of RQ1 have shown that the 65+ demographic are only partially achieving recommended temperatures, but participants reported comfort at these temperatures. Furthermore, Chapter 4 has shown that Fanger's PMV/PPD model is not suited to predicting thermal comfort of this demographic in heating seasons.

Research Question 2, discussed in Chapter 5, investigated how older people cope in cold homes and the strategies they implement to achieve thermal comfort and maintain health during winter periods. By conducting interviews in a subset of known cold homes this RQ was answered. In line with other studies (Chard and Walker 2016, Day and Hitchings 2011, Monroe et al. 2007, Devine-Wright et al. 2014), findings showed that older people's habits do play a key part in shaping their view of thermal comfort, with a resilience to manage, even if it may not be conducive to health. Concerningly, extreme and sometimes dangerous strategies to cope in cold weather were identified with clear concerns over safety. The interviews highlighted a need for more support than is currently offered, especially relating to securing a fair price for energy provision. Furthermore, as other studies have found (Boardman 2010), there is evidently need for better targeting of financial aid to ensure that those most in need receive sufficient financial assistance that enables them to afford fuel to maintain temperatures that safeguard health. Another possible remedy highlighted in the interviews was the potential for retrofit schemes tailored to older people. This is not something that is perceived favourably in the literature (Claudy et al. 2010, Willis et al. 2011), however, If schemes were designed with older people in mind then the benefits could be two-fold. Firstly, if already comfortable, older people would be able to achieve their current temperatures at a lower cost and lowering emissions, with a clear environmental benefit of reducing space heating demand. Secondly, older people who are not currently able to afford sufficient heating to safeguard their health would be able to achieve higher temperatures for the same level of expenditure, theoretically protecting their health. Given that older people are the demographic known to spend the longest periods in their homes, it is clear they should become a focal point for retrofit schemes, as there are evident benefits in this demographic, more so than others.

Finally, Research Question 3 focused on thermal comfort in summertime, aiming to identify what temperatures were achieved by the 65+ demographic in summer, how comfortable they were, how accurately the PMV/PPD and adaptive models were able to predict comfort and whether the older people were suffering from overheating in the participating homes (37 homes in 2017 and 16 homes in 2018), with results discussed in Chapter 6. In 2017, 91% of TSV votes were between [-1,+1] and in 2018 this figure was 89%. Given the contrast in temperatures between the two years, the similarities in comfort are interesting and suggest that older people are capable of adapting to their environment, perhaps more capable than literature would suggest (Adams 2008, Donald 2009). Findings showed that neither the PMV/PPD model nor the adaptive model were able to accurately reflect thermal comfort. For the PMV/PPD model, in 2017 mean PMV was -1.2, whereas mean TSV was +0.1, and in 2018 mean PMV was -0.5 whereas mean TSV was +0.3. For the adaptive model, in 2017 of the 91% of TSV responses reflecting comfort, 28.6% were within the Category I parameters, and in 2018 this rose to 53.5%. The overheating metrics of TM59, TM52 and Guide A were used to identify instances of overheating. As anticipated, more homes failed TM59 in the extreme summer of 2018 compared to the typical summer of 2017, however, the majority of TSV votes fell in the comfort range for both summers. Although it is important to recognise that the external temperature was not especially high at the point when TSV was reported by participants.

This RQ has shown that both models do not accurately capture the thermal comfort of older people, which is especially concerning in relation to the adaptive model as it provides the basis for the overheating metrics. It is clear that further research into overheating analysis in homes occupied by older people is necessary.

Chapter 8

Limitations of the study

The findings of this thesis have to be interpreted bearing in mind some limitations. One of the main limitations lies in the measurement of variables used in calculations for the thermal comfort models, in particular air temperature, relative humidity and thermal insulation (clo). Whilst iButtons provide an unobtrusive and cost-effective method of measuring air temperature and relative humidity and are used in similar studies, there are inherent limitations in their use. Primarily, they are only able to capture the temperature in their immediate environment and hence do not capture the temperature fluctuations within a room. When considering there are temperature differences between different areas of the same room, it is possible that the room occupant at the time of answering the questionnaire experienced a different temperature than the sensor recorded, which may have a bearing on the PMV/PPD output. However, the actual influence of this on the PMV/PPD output is minimal, as given a certain met rate and clo value, changing the temperature by 1°C either increases or decreases the PMV output by 0.3 (ie. for met rate of 0.9 and clo of 1.0, PMV at 17°C is -2.3, PMV at 18°C is -2.0, PMV at 19°C is -1.7 and so on. See Appendix 10 for outputs). Furthermore, another limitation relates to metabolic rate being assumed and mean radiant temperature considered to be the same as air temperature in the PMV/PPD calculations, which limits the accuracy of the results of the PMV/PPD output.

Another limitation relates to the size and demographic of the sample. The participants were generally healthy and homogenous, it is probable that people aged over 65 in worse health would not be fit or able to participate in such a study, and this could potentially have influenced the health sections of the thesis. It is therefore important to bear in mind the sample is overall a healthy group of 65+ year olds when looking at the findings on health in the thesis. Furthermore, the sample size is too small to enable statistically significant findings from the results.

A further limitation relates to the frequency with which the questionnaires were answered. It was necessary to balance the questionnaire dissemination frequency with the likelihood of participant fatigue, especially as the participants were not incentivised or remunerated for their participation. Hence, a monthly frequency was decided upon, however, it is important to realise that participants may not have remembered entirely accurately responses to the questions, such as frequency of access to healthcare, over a time period of a month.

Chapter 9

Conclusions and Future Work

This thesis has presented the findings of the first UK longitudinal temperature monitoring study to focus exclusively on the 65+ demographic, which aimed to create a better understanding of the internal temperatures achieved, thermal comfort of participants and its influence on health in this demographic. The work was conducted as a result of recognising that older people are said to be most vulnerable to the harmful effects of extreme temperatures found in their homes. Despite this, the internal temperatures and thermal comfort in this demographic has received little research attention, hence, it was not known what internal temperatures are achieved, whether they meet recommendations, whether occupants were comfortable and what effect, if any, the internal temperature had on health. This thesis has built on current temperature monitoring studies by using similar methods, but focusing on the 65+ demographic to answer these questions.

Based on the results presented in Chapter 4, self-reported TSV clearly contrasted with outputs from the PMV/PPD model, which was found to significantly under predict the true comfort of the participants. Nonetheless, the findings in Chapter 5 showed the need for more support networks, fairer energy provision for older people, the possibility of retrofit schemes and better targeting of financial aid; all of which are potentially likely to alleviate some of the older people's struggles. For summer periods, the results presented in Chapter 6 show a similar situation to the findings of Chapter 4, where both the PMV/PPD and adaptive models were not able to accurately predict participant thermal comfort, with the majority of TSV votes falling within comfortable parameters for both summers.

Overall, this thesis has shown a clear contrast between thermal comfort models and self reported comfort of older people for both heating and cooling seasons. This has clear implications for under and overheating analysis, as the failure of both models to predict thermal comfort in older people highlights that current thinking around recommended internal temperatures, predicted comfort values, health and the influence of the older people themselves needs to be reassessed. Currently, two major global challenges are ageing populations and climate change, so reevaluating strategies to ensure that older people are able to achieve thermal comfort within their homes has the potential to enable older people to successfully age in place without risk of unnecessary harm whilst potentially mitigating unnecessary emissions through reexamining recommended temperatures.

The work presented in this thesis provides sufficient evidence that mechanisms to ensure older people achieve thermal comfort, for instance recommended internal temperatures and financial assistance, require reconsideration to better reflect the ageing population. As a result, further research areas have become more evident, especially the need for a larger scale, nationwide investigation into thermal comfort of older people, with an increased number of participants. Conducting this investigation would enable a broader reflection of thermal comfort across the UK, encompassing, for instance, different external temperatures, levels of wealth and healthcare trusts, all of which would be valuable. Furthermore, it is clear that more research is necessary into the health implications of under and over heated homes in this demographic, as although no health effects were observed in this study, the strength of the literature suggests that there are clear problems, especially in the very old, who may be especially vulnerable.

Another possible future study would be to investigate the thermal sensitivity of older people using a climate chamber. Through exposing participants to a range of temperatures and altering their activity level and clothing, then asking them to respond to thermal sensation questions, their TSV could be compared to PMV outputs for different temperatures, met rates and clo values. At present there are differing conclusions about the thermal sensation of older people, so a study of this nature would be beneficial.

Furthermore, it is believed that 80% of the Winter Fuel Payment is distributed to people that do not need it (Boardman 2010). It is clear from this research that older people feel they would benefit more from support and guidance organisations offering assistance with problems such as securing the best energy tariff, especially as today this tends to be conducted online, which Chapter 5 showed can cause anxiety in the older demographic due to unfamiliarity. Perhaps the Winter Fuel Payment not going to older people in need could be redirected into funding a support network for older people or alternatively into retrofit schemes for older people. This highlights another potential future area of study in investigating whether the Winter Fuel Payment should be reanalysed in light of the fact that a high proportion of it is not used as intended and how best the 'wasted' portion should be allocated to assist the most vulnerable of older people.

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Appendix 1 - Fanger's PMV/PPD Model Equations

The literature review introduced Fanger's PMV/PPD thermal comfort model. The following four equations are used, in accordance with ISO 7730, to calculate the PMV and PPD. The code was validated by checking the calculated outputs were the same as the example output in ISO 7730 Annex D.

Equation 1:

$$\begin{aligned} &\mathrm{PMV} = [0.030 \cdot \exp(-0.036 \cdot \mathrm{M}) + 0.028 \\ &(\mathrm{M}-\mathrm{W}) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (\mathrm{M}-\mathrm{W}) - \mathrm{Pa}] - 0.42 \cdot (\mathrm{M}-\mathrm{W}) - 58.15 \\ &- 1.7 \cdot 10^{-}5 \cdot \mathrm{M} \cdot (5867 - \mathrm{Pa}) - 0.0014 \cdot \mathrm{m} \cdot (34 - \mathrm{Ta}) \\ &- 3.96 * 10^{-8} \cdot (\mathrm{Fcl}) \cdot [(\mathrm{Tcl} + 273)^4 - (\mathrm{Tr} + 273)^4 - \mathrm{Fcl} \cdot \mathrm{Hc} \cdot (\mathrm{Tcl} - \mathrm{Ta}) \end{aligned} \tag{1}$$

Equation 2:

$$\begin{aligned} &\mathrm{Tcl} = 35.7 -).028 \cdot (\mathrm{M}-\mathrm{W}) - \mathrm{Icl} \cdot 3.96 \cdot 106 - 8 \cdot \mathrm{Fcl} \cdot [(\mathrm{Tcl} + 273)^4 \\ &- (\mathrm{Tr} + 273)^4 + \mathrm{Fcl} \cdot \mathrm{Hc} \cdot (\mathrm{Tcl} - \mathrm{Ta}) \end{aligned} \tag{2}$$

Equation 3:

$$\begin{aligned} \text{Hc} =& 2.38 \cdot (\text{Tcl} - \text{Ta})^{0.25} \text{for} 2.38 \cdot (\text{Tcl} - \text{Ta})^{0.25} > 12.1 \cdot \sqrt{\text{Var}} \\ & 12.1 \cdot \sqrt{\text{Var}} \text{for} 2.38 \cdot (\text{Tcl} - \text{Ta})^{0.25} < 12.1 \cdot \sqrt{\text{Var}} \end{aligned} \tag{3}$$

Equation 4:

$$\begin{aligned} \text{Fcl} &= 1.00 + 1.290 \cdot \text{Icl} \text{for} \text{Icl} < 0.078 \text{m}^2 \cdot \text{K/W} \\ &= 1.005 + 0.645 \cdot \text{Icl} \text{for} \text{Icl} > 0.078 \text{m}^2 \cdot \text{K/W} \end{aligned} \tag{4}$$

Where:

M is the metabolic rate ($Wm^{-2}K$).

W is the external work ($Wm^{-2}K$).

Icl is the clothing insulation (Clo.)

Fcl is the clothing surface area factor.

Ta is the air temperature (°C).

Tr is the mean radiant temperature (°C).

Var is the air velocity (ms^{-1}).

Pa is the water vapour partial pressure (Pa).

Hc is the convective heat transfer coefficient ($Wm^{-2}K$).

Tcl is the clothing surface area temperature (°C).

Appendix 2 - Demographic Characteristics of Participants

A demographic breakdown of all participants in Table 1 suggests that there is a diversity of age-class, annual incomes, house types and house ages, with little systematic bias.

Table 1: Demographic Characteristics of Participants

Demographic Characteristic		Number of Participants
Age	60-69	15
	70-79	16
	80-89	9
	90+	3
Gender	Male	14
	Female	28
Number of Occupants	1	28
	2	12
	3	3
	4+	0

Income (£)	Less than 6000	1
	6-13000	11
	13-19000	9
	19-26000	8
	26-32000	2
	32-48000	5
	48-64000	1
	65000+	1
Education Level	None	5
	GCSE	6
	A Levels	3
	Degree	8
	Postgraduate Qualification	4
	Professional Qualifications	17
Tenure	Owner Occupied	36
	Private Rented	4
	Social Rented	3
House Type	Detached	10
	Semi-Detached	14
	Terrace	10
	Flat	7
	Bungalow	1
House Age	Pre-1919	15

	1920-44	4
	1945-64	11
	1965-84	6
	1985+	7
Wall Type	Cavity	26
	Solid	15
Insulation	Yes	19
	No	24
double Glazing	Yes	33
	No	10
Central Heating	Yes	42
	No	1
Fuel Type	Gas	35
	Electricity	6
	Solid Fuel	2

Appendix 3 - Clo values of clothing garments

Table 2: CLO values of individual clothing garments, in accordance with ISO 7730.

Garment description	Thermal Insulation (Clo)
Underwear	
Pants	0.03
Underpants with long legs	0.10
Singlet	0.04
T-shirt	0.09
Shirt with long sleeves	0.13
Pants and bra	0.03
Shirts/Blouses	
Short sleeves	0.15
Lightweight, long sleeves	0.20
Normal, long sleeves	0.25
Flannel shirt, long sleeves	0.30
Lightweight blouse, long sleeves	0.15
Trousers	

Shorts	0.06
Lightweight	0.20
Normal	0.25
Flannel	0.28
Dresses/Skirts	
Light skirt (summer)	0.15
Heavy dress (winter)	0.25
Light dress, short sleeves	0.20
Winter dress, long sleeves	0.40
Boiler suit	0.55
Sweaters	
Sleeveless vest	0.12
Thin sweater	0.20
Sweater	0.28
Thick sweater	0.35
Jackets	
Light summer jacket	0.25
Jacket	0.35
Smock	0.30
Outdoor clothing	
Coat	0.60
Down jacket	0.55
Parka	0.70
Fibre-pelt overalls	0.55
Sundries	
Socks	0.02

Thick ankle socks	0.05
Thick long socks	0.10
Nylon stockings	0.03
Shoes (thin soled)	0.02
Shoes (thick soled)	0.04
Boots	0.10
Gloves	0.05

Appendix 4 - iButton Calibration Testing

Testing of the iButton sensors was conducted in a climate chamber, spanning a temperature range of between 15°C and 25°C every hour with RH remaining constant at 50%. Figure 1 shows that at higher temperatures there is a 1°C difference between the sensors, with half reading on average 25°C and half reading on average 26°C, the accuracy of the sensors is only ±0.5, so the observed difference is within measurement accuracy. It is also possible that the sensors recording 26°C were closer to the heating element of the climate chamber.

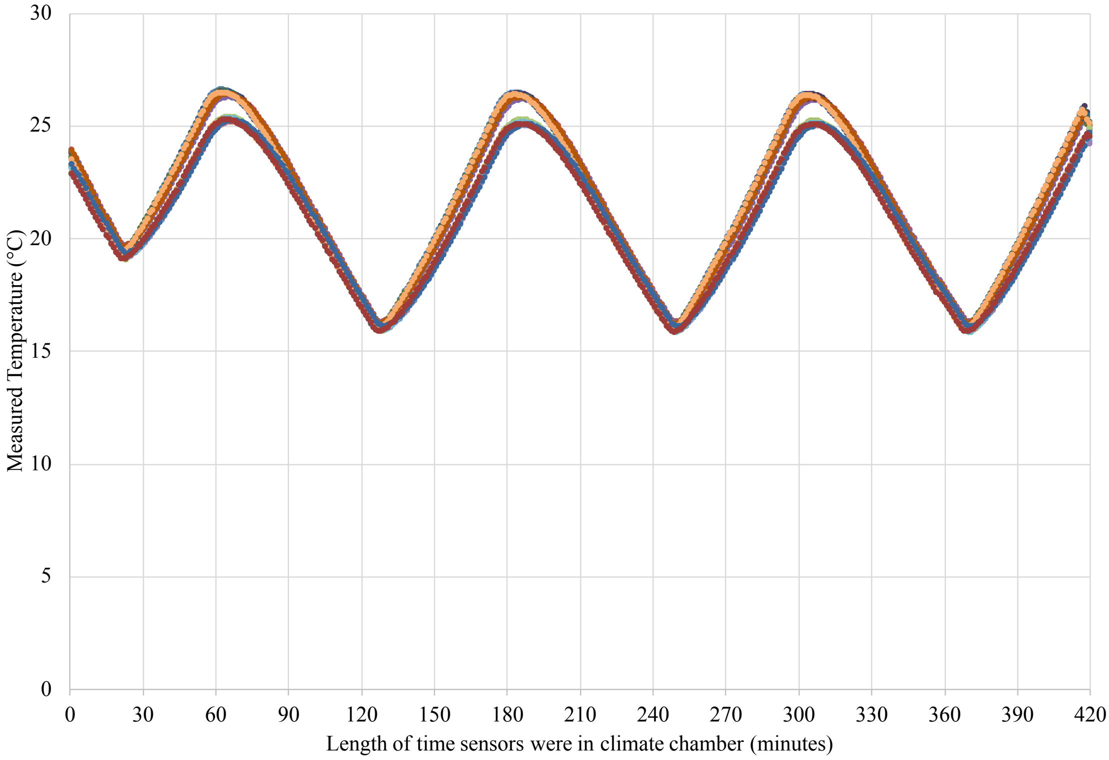
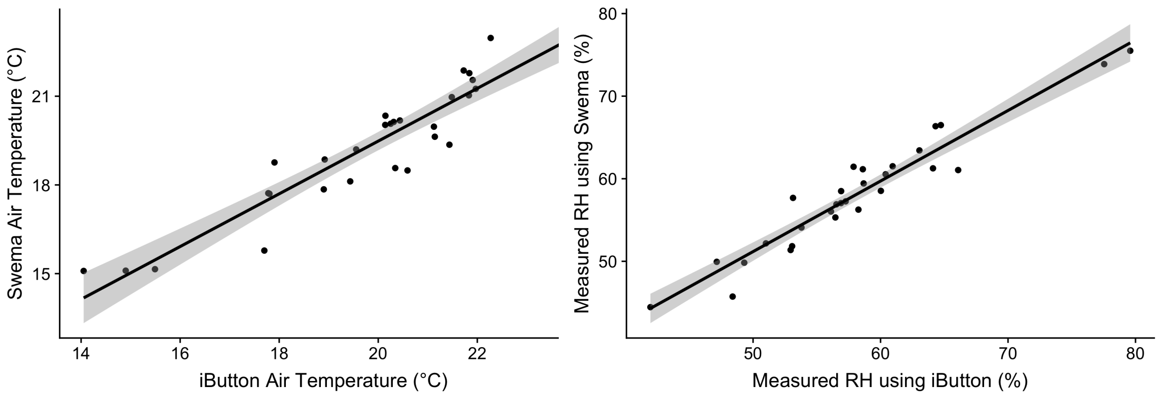


Figure 1: Testing of iButton sensors programmes to record every 60 seconds in a climate chamber spanning between 15°C and 25°C every hour with RH set at 50%.

In addition to the laboratory tests, periodic field validation was carried out throughout the study period using the Swema equipment, which complies with the ISO7730 standard (see Appendix for image and exact model). These data suggest that sensor performance matched laboratory tests with a strong correlations for both temperature (R^2 = 0.86, Figure 2a) and relative humidity (R^2 = 0.91, Figure 2b). This suggests that iButton data are reliable and appropriate for use in measuring thermal comfort.



(a) (b)

Figure 2: (a) Linear regression, with trendline, of indoor mean living room air temperature (°C) and (b) Linear regression, with trendline, of relative humidity (%), measured using the iButtons and BS EN ISO 7730 compliant Swema equipment, measured in November 2016.

Finally, the manufacturer's data sheet suggests minimal time drift of the real time clock of the DS1922L-F5 at the temperature range observed in the study (8-23°C) (Systems 2015), so the observed readings can hence be considered accurate for the time that they were recorded. This is essential in order to accurately correlate measured temperatures against subjective data from our surveys.

Since the radiator sensor is designed to measure the heating system's time of operation rather than the radiator's temperature itself, its required accuracy was not deemed to be of the same order as those for the living and bedrooms. Hence, the iButton DS1921G-F5 was selected with an accuracy of ± 1 °C, a range of -40 °C to +70 °C, a measurement interval of 1 to 255 minutes and a reading limit of 2048.

Appendix 5 - Interview Transcripts

ANNE:

I: So the first question is are you comfortable with the internal temperature in your home?

A: Yes.

I: What do you do to feel comfortable?

A: Well, I wear slippers all the time, and I've got supplementary heating which I use when I need it. I don't have it on overnight, I just put it on and off when I'm in the sitting room.

I: Do you feel the cold more now than when you were younger?

A: I haven't noticed any difference to be honest. No.

I: Do you ever notice the cold affect your health? So any worsening or circulatory problems, or arthritis if you've got it?

A: Well possibly, I think I have got some arthritis in the knee, I've had injections in both knees now at different times and I think that is possibly due to arthritis. But it doesn't worry me too much, but I think if there is a change in temperature and it gets wet or cold then I think it can make a difference.

I: So is it the dampness rather than the cold that you find worse?

A: Probably, yes, I mean I'm not very, I'm still fairly new to this, I never used to suffer with arthritis at all, but as you get older you're bound to get these things aren't you. It isn't all the time though. Once I had the injections though it was better. They're certainly not bad enough to have knee replacements, but if it got that bad I'd have to have that done.

I: If you were feeling cold would you choose to turn the heating up or put on an extra layer?

A: I'd put on an extra layer first, I've got a sort of waistcoat thing that I'd put on or another thing that I knitted with holes in, which is the warmer of the two. I tend to only have about two layer on at any time though.

I: If you did put on the extra layer, why would that be your reaction to the cold and not turning up the heating?

A: It's funny isn't it, I suppose I just think oh it's cold today I'll put this on. I mean I have done it more this winter than I normally would. But um, turning up the heating isn't something I would think of as there isn't a control, I just switch it on when I'm in the room and off when I'm not usually.

I: How much do you use extra sources of heat? Obviously you use the fire sometimes.

A: Well, I use the fire as there's nothing else in here. I have actually kept the convector heater on all the time in the kitchen at the moment, which I normally don't do. It's a small-ish room so it doesn't use much heat but it does mean that when I come down in the morning it's nice and warm.

I: Do you ever use things like hot water bottles or blankets?

A: I have an electric blanket, yes, that I put on when I go up to bed. It's only on for perhaps 15 mins. But no I never use a hot water bottle or blankets downstairs or anything like that. I've never done that, no, no.

I: How willing would you be to take up new technologies, so things like PV panels on the roof?

A: I don't know, we did think about solar panels, to the extent we did get a man in to tell us all about it, um, but in the end we decided we wouldn't, but I was quite keen actually at that time, but I haven't really done anything about it now and I don't know that I would be bothered to really. I suppose if I was, I wouldn't be against it if anybody wanted to do it, but I don't think I'd feel that keen to do it. I never really know how long I'm going to stay here, it is far too big for one person and you feel there's all these families needing houses and it just feels a bit selfish to stay, but on the other hand every now and again I think, because I thought about these new places in Mulberry park, to downsize, but then you get so used to your kitchen and I think do I really want to change.

I: Also, probably lots of your happy memories are in this house.

A: Yes, that's true, but I don't think that worries me as it might do some people, but, um, and I must admit although the garden is a bit of a problem I do love it and I wouldn't want to go anywhere without a garden of some kind, but a smaller one would be better really, um, and I say, not that I'm looking but if another property happened to come up and I thought oh that's nice then I might consider it and obviously I know people who have left it too late to move and at the moment I've still got a reasonable amount of ability that I could move without too much trouble, but um so, but anyway there we are.

I: In the very cold weather, like when it snows, how do you manage? Do you cope alright with everything?

A: Well, yes, I suppose it didn't last long and they did warn us that it was coming so I made sure I got food and everything in. But the only thing was the milkman didn't come, but I was planning to walk in it, as I love the snow. But then some couple from church were coming back from Tesco and they offered to go and get some milk for me, so they did. Then somebody else knocked on the door and offered to clear my path, and so they did. They made it beautifully clear, so people are quite helpful, um, as I say I didn't need to go out so I just stayed put.

I: Are there any other things that worry you when it gets cold?

A: No, I don't think so, I think my circulation is quite good so that must help, but again maybe when I get into my 90s I might start to feel really cold. I visit a 98 year old over the road who wears several layers and has the house really warm, and she needs it that hot to keep going, but I always feel it would be too hot for me. Anyway, I'm not in my 90s yet.

CATHERINE

I: Are you comfortable with the internal temperature inside?

C: Yes, I'm sure it could be better, but um, yes.

I: And what do you do to feel comfortable? Do you use blankets, hot water bottles?

C: Um no, if it's really cold, cos it tends to be warmer upstairs, I mean the heating is set to come on at 8pm every evening, but in the winter or if it's really cold and I come back at 4pm and it's cold then I override it, but if I'm just sitting here and I'm fine in the evening and it's not too cold then I might just wear an extra jumper, um or a scarf, I don't sit with lots of hats on or anything like that and then I just override and put the heating on early.

I: Do you feel the cold more now than when you were younger?

C: Probably yes, yeah.

I: Is that in your hands and feet, or across your shoulders?

C: I think it's probably my feet first, yeah, and then you just generally feel 'Oh' I'm not comfortable.

I: What age did you first notice that you were feeling the cold more?

C: Oh, goodness me, um, probably in my 60s.

I: Do you ever notice the cold affect your health? For example circulatory problems getting worse or arthritis getting more achey?

C: No, I haven't got any of those problems, yet!

I: If you were feeling cold, would you choose to turn up the heating or put on an extra layer or both?

C: I would put an extra jumper on to start with, but then if I'm feeling cold and I'm sitting down the I'd put the heating on, and certainly in the winter I would turn it on and override it by an hour or two, whenever I start feeling cold.

I: How much do you use extra sources of heat? So do you ever use another heater or a blanket?

C: I've got a gas heater in the sitting room, but I very rarely use it. I remember turning it on when my daughters were here, I would put it on when they start gathering jumpers around them, but I'm sure it's been on maybe twice the whole of this winter. So, just because of saving money and I don't feel that cold, you know, if I was really really cold and it was icy outside then I would use it but no, I haven't used it more than twice this year.

I: How about blankets or hot water bottles?

C: I've got a few blankets around the place, but I don't no, I think there's heating underneath the floor, upstairs I think, so I never use them. I don't like the feeling of getting into bed and it's too hot.

I: How willing would you be to take up new technologies, so things like PV panels, or anything on the roof.

C: I'd love them to put things like that on, I think once the people came to look and they said the house was facing the wrong way and then my friend told me about, um, some technology where you can change which side of the house these panels are on, but that must be quite new, I'm amazed that there aren't more houses with those solar panels on, anything else, I don't know what other technology there would be. I don't like the idea of, um, turning your things on from your mobile phone, I don't like that at all.

I: How come?

C: I don't know, it's just anti-technology I suppose. Too much technology.

I: Is it the thought that someone could get in and get access?

C: Yeah, it's the security thing.

I: If you did install PV panels, in theory, would you use the energy savings to have a higher internal temperature or would you save the money?

C: I think it depends, I don't think I make myself miserable with the amount of heating I have in the house, so probably not initially, but it depends what the climate does. I suppose if I started feeling cold I would. But if things stayed the same as they are then I wouldn't.

I: In the very cold weather how do you tend to manage? So when it's snowy outside, is it reasonably easy to keep the house warm?

C: Yeah, I manage, I just close everything down, and if it's really cold then I close the curtains and keep the heating on low.

I: In relation to energy bills, do you switch or stay on the same one?

C: No, I wish I had an advisor to come and do things for me and tell me "oh this is better" because to compare like for like is very difficult, it's just so intricate, it's not easy to swap, it's like with insurance policies, when you think oh well is that included in that, so have I got a better deal or haven't I, and as far as energy goes, I've kept on this one for at least 4 years, and I think it's gone up, because usually I have a big credit but this time I haven't. I pay about £90 a month for gas and electric and for the last three months I've overspent by about £5, which has never happened before.

I: Is that partly because it's been colder for longer so you've used more heating?

C: No, I think I've used roughly the same, although no one's said anything.

I: Are there any other things that become worrisome in the cold weather?

C: Not really, I mean I've worried about going out, but I've got some really good tread boots, because I did once fall over. Also, when it's snowy I have a neighbour who comes and checks on me. But no I don't have any worries heating or health wise.

ELIZABETH:

I: Are you comfortable with the internal temperature in your house?

E: Yes

I: What do you do to feel comfortable?

E: It depends really, if I know I'm going to sit for the evening, I'll put the heating on. If I'm sitting at lunchtime watching the news or whatever then I'll add a jersey or a scarf. Make sure I've got a thick jumper on.

I: Do you feel the cold more now than when you were younger?

E: I do, yeah.

I: In what ways, is it hands and feet or a general chill?

E: Yeah, hands and feet, hands and feet. And around my shoulders, which I never used to take any notice of. I've got a little scarf I wear.

I: What age did you start noticing that you felt the cold more?

E: Oh probably only the last, well hands and feet probably only the last 8 or 9 years, but the neck and shoulders is relatively recent, say 2 or 3 years.

I: Do you ever notice the cold affect your health?

E: Not really, even though this year has been colder, um, I did have a period where I had chill blains, not this year though. Up until about 5 years ago I'd never had a chill blain at all. I don't know how though; I don't possess a hot water bottle or anything.

I: If you were feeling cold would you decide to turn the heating up or put on an extra jumper?

E: Um, if it's in the day I'd put on an extra jumper and I tend to have it on between 18 and 20°C and I really don't need to alter it. I don't think I've ever altered that.

If I come in and it's bitterly cold I would put it on 25°C just for a little bit and it heats up quickly, but I do control it just by the thermostat.

I: It is pretty well insulated this house though, isn't it?

E: Yeah, and I've got insulation in the walls and the loft.

I: So I think I probably know the answer to this one too, but how much do you use extra sources of heat? So blankets, extra fire.

E: Well, definitely, the last two or three winters, when it gets really cold, I use flannelette sheets and my sleepwear will be slightly thicker.

I: But in the daytime do you have any blankets down here or anything?

E: Oh no, I've got a little grey scarf and I will use that when it gets a bit colder, it's surprising how warm it is. It's reputing to be cashmere. I'll also keep my slippers and socks on whereas in the summer I'm barefoot.

I: The next question is about taking up energy saving technologies, like PV panels, but you've got them already haven't you?

E: Yeah, I've got them already and insulation.

I: In the very cold weather, how do you manage? Is it alright in the house?

E: Yeah, I manage, I'm fine really in the cold.

I: Are there any other things that ever worry you in the cold weather.

E: No, I mean these two spells of snow we've had, I mean, I just, we were given plenty of warning, so I got enough supplies in.

JAMES:

I: Are you comfortable with the internal temperature in your home?

J: Not always, no. I seem to have a bit of a draught problem, so, literally it depends on where the wind's blowing from. Part of the problem is the previous owners of the house opened up the two downstairs rooms into this big through lounge and I regret that now, because I wish I had a smaller room, in fact the room above that front room, the bedroom, is actually the warmest in the house but it's about the only one.

I: Oh really!

J: Yes, and it's only got one little radiator in the corner, but it's because it does just sort of close up into a smallish room. And I think my bedroom is cooler, but I do have the radiator turned right down in there because I don't want it too hot. So yeah, sometimes it seems cold, when I get draughts coming through and then I'm not always happy with the temperature, other times I am.

I: What do you do to feel comfortable?

J: Um, put on the electric fire and sit quite close to it!

I: Do you feel the cold more now than when you were younger?

J: Oh yes, definitely.

I: In what kind of ways?

J: Um, literally, just feeling a little bit cold round the shoulders type of way, yeah. I find in this cold weather, I've got a very warm jacket, um, but even in that if I go out and walk down to the shops and back, I'll feel it a bit these days.

I: When did you first notice this?

J: I would say quite a while ago, anything up to about 10 years ago, I'm 65 now, so when I was 55.

I: Do you find any health problems get worse during the cold, including your arthritis?

J: Well, the first time it really hit me was last winter, er, and I suffered for about 3 or 4 months from mid-December onwards, it was horrible and as I say, this year from mid-December onwards, I've been almost clear of it and I thought I've really got away with it this year, but I've now, just this last couple of days, got quite nasty pain in the left leg, all the way up and down it. My GP diagnosed it as osteoarthritis in the knees, or at least some of the pain is that. What I did find was going out for short bike rides had a wonderful effect on it, just little 2 mile bike rides for about 10 or 15 minutes, um, so I must get back and do those again. I haven't been doing them recently as it's been so cold.

I: Well you can't really do it with the snow, it's a bit too dangerous.

J: Well, I mean 10 years ago, when I was merely 55 I used to go out on quite long rides, 10 to 15 mile rides and there would be frost forming on my jacket on the cycle path, but I couldn't do that now. I remember I took to riding on the two tunnels route, out towards Wellow, and I remember, I think it must be the winter before last possibly, and I went out wearing what I would normally wear, but I was shivering and I thought no this is too cold, I'm not up to this anymore. I knew it was no colder than it had been other years, but I just thought this is me, that's what's changed, I can't cope with it anymore. But there you go.

I: Do you find the cold affects any other problems, like any kind of circulatory or respiratory problems?

J: Um, I don't think so, I've had a very good year in terms of, I haven't had flu or a serious cold or anything. I think it's actually warmer in this house than I think it is. We've got an Age UK heat sensitive christmas card and it always says 21C, when

I've got the heating up in the evening, so it's never saying well it's only 18C, you should be a bit warmer, but I think again it's psychological a little bit, I've got used to the draughts and I always feel a bit chilly. Although when I go up to [partners] place, which is a lovely warm sealed up flat, I quite often feel a bit cold there too, you know, so I just think it's me, I think I'm just a bit sensitive to the cold.

I: So, if you were feeling cold, would you choose to turn up the heating or would you put on an extra jumper?

J: I would turn up the heating but only because, you can see what I've got on, a vest, a t-shirt, a pullover and a cardigan on so as far as I'm concerned I'm almost dressed for the outdoors anyway and it's in that context that I feel comfortable enough with the electric fire on. My only backstop on this now is that I only put one bar on the electric fire, so I could double that if necessary, although I haven't had to do it for a couple of years now. It's not so bad.

I: How much do you use extra sources of heat, obviously you use the electric fire, do you ever use things like blankets or hot water bottles?

J: No, I've got a tog 13 duvet which I find enough. I use it all year round, I don't have a lighter one for summer or anything.

I: Do you have an electric blanket aswell?

J: No, I find the duvet good enough.

I: How willing would you be to take up new technologies, like PV panels?

J: Oh entirely willing to do it, it depends a little bit on the cost, you know, the cost to performance ratio of it but um, yes unfortunately this house, it um, is not very well suited to roof mounted panels because it is almost due east. I suppose you could put some on the front and get something from there, but um, yeah.

I: In theory, if you did install panels, or something similar, would you use the energy savings to have a higher internal temperature or would you just save the money.

J: I think the problem is that I don't think it's actually possible to raise the temperature in here much more, because of the age, I mean if I wanted to raise the temperature I would spend the money on draught exclusion and possibly window replacement, as that's where the problems are. I've had to tape up the bathroom window this winter, because when it was very cold and the wind was coming from the east, which of course is the colder wind, um, the seal seems to have gone on it and I put my finger up to it and it was like there was an arctic gale blowing past it and so I sealed it up with parcel tape and it made quite a big difference. And of course I had new patio doors put on the back there in September and that's made a huge difference.

I: Oh yeah, I remember you showing them to me last time I was here.

J: It's really made a difference.

I: In the very cold weather, like when we had the snow before and now, how do you tend to manage? Do you ever worry about not being able get out or being too cold in here or anything like that?

J: The house has been surprisingly warm during both sets of snow, because as I say it tends to be more affected by wind than the actual ambient temperature which is a bit odd, but you get used to it. Um, and no I haven't worried at all about getting out, er, because we're so close to the A4, the main road there, and we're on the flat, so you know, we don't live up a hill, we don't live miles from any kind of road, we're right next to the main A4 trunk road and so if anyone's going to get through I'll be able to get through, but um, there we are yes. So no, I haven't felt sort of snowed in here.

I: Do you ever do things like heat less rooms? Or stay in bed for longer periods?

J: Um, heat less rooms, I've got thermostatic valves on all the radiators, so I have turned some of them down a lot, particularly the bedroom, which is right down, um and the passageways, so to that extent I adjust it room by room, but um as I say the big problem is this large expanse here.

I: I suppose because you've got the door here, and windows, it's sort of a through draught.

J: There is and the other thing is these old floorboards they're not tongue and groove so I mean if you come in this room in darkness and turn the lights on in the cellar, it's quite dramatic.

I: Are there any other things that become worrisome when it's cold?

J: Well, one thing we've done, you can see that rather theatrical looking screen there, that is to protect me, there's a chair behind there, but the screen and the drape over it, they are there because I was getting a particularly nasty cold draught which was making my ear go numb, so that saved the day, and again I'm a bit worried that if I took the screen away I might feel the draught even if it wasn't really there, but I mean I did once have some joss sticks, but the column of smoke turned almost horizontal there was that much of a draught. There are two open chimneys in this room, which again don't help and they're alright but they're designed to have fires.

JANE:

I: So the first question is are you comfortable with the internal temperature in your home?

J: Yes

I: And what do you do to feel comfortable, use blankets, slippers anything like that?

J: What do I do to feel comfortable, I adjust the thermostat and turn the heating on or off.

I: Do you feel the cold more now than when you were younger?

J: Yes

I: What age did you first notice that start to happen?

J: Um, I'm not sure I could say really, it's just been a gradual process, and I did feel the cold when I was younger so I've always felt the cold. But I do feel it more now. I think it just depends whether I've been active, if I've been out for a walk, your system gets going, if I'm just around the house on a very cold day you tend to stay a bit colder.

I: Do you ever notice the cold affect your health, say worsening of arthritis or circulatory problems?

J: No.

I: So you've sort of slightly answered this already, but if you were feeling cold would you choose to turn the heating up or put on an extra layer or do both.

J: Both, but I often wear a few layers anyway – I don't take many chances! Usually two layers, and a layer of wool. The wool is the secret.

I: Do you ever buy cashmere? It's very warm although it is expensive.

J: Not to keep warm it isn't, I'd pay to keep warm!

I: How much do you use extra sources of heat, so things like blankets, hot water bottles, electric blankets, that kind of thing?

J: Really only the electric blanket at night.

I: How willing would you be to take up new technologies, like PV panels?

J: Well, I already have that. Yes, but not all these things in the house, I don't fancy getting my house all electronically managed. Like Hive and things like that, I saw an advert on TV where it organises everything, and I don't like that.

I: In the very cold weather, so when it snows, how do you manage?

J: The house copes very well, it retains heat, and I'll maybe put on an extra layer or wear socks as well as slippers and tights.

I: With energy bills, do you tend to stick with the same supplier or switch?

J: I don't switch much, no.

I: Is that because you're happy with the current supplier, or because you don't like the thought of having to switch?

J: The bills aren't terribly high, so it's not a huge saving and the other thing is I've gone for an ethical provider so someone who supports alternative sources of energy.

I: Which one do you use?

J: Good Energy. So I'm not incentivised to change much, on either count. Frankly though, I can't understand their bills and I can't understand how they're billing me and then they must have overcharged me and they cut it all down to £20 a month and then it's gone up again and now I seem to owe them, so I'm completely confused, so I don't even try and understand it now, they'll sort it out when I move house!

I: Are there any other things that worry you when it gets cold?

J: The slipperiness outside.

JENNIFER:

I: So the first question is are you comfortable with the internal temperature in your house?

J: I put up with it, I wouldn't say I'm comfortable, but I put up with it.

I: What do you do to feel comfortable?

J: I go to bed with a hot water bottle.

I: In the daytime?

J: In the daytime, well you see I've got a rug there, and I tend to wrap myself up and I put a hot water bottle on my body and sometimes I even have one on my feet and I put my feet up and then I can be comfortable for upto 4 hours. I'm quite good at managing to keep warm, and I do get up quite a lot to move around or get a hot drink.

I: Do you feel the cold more now than when you were younger?

J: Oh yeah, yeah, well I think maybe it's because I also suffer from Raynaud's, which is a circulation problem, and you're extremities are always cold so consequently your body can't get warm enough.

I: Do you feel warm enough now?

J: Yeah, well I think I move about a lot, I don't really sit down.

I: What age did you first notice that you felt the cold a bit more?

J: I would say in the last 10 years, I would say 65 years onwards.

I: And how long have you lived in this house for?

J: 27 years, I can't afford to move. It's not practical though.

I: In what ways?

J: Well, because the insulation is bad and it's old, the front door is the original door from 1875, and it's warped and there are great big gaps where the wood has shruk, but I can't afford to replace it because it's not a standard door, it's not something I can go and buy off the shelf.

I: Is it listed?

J: Yes, so it makes it difficult, I can't do anything like put double glazing in. So I just try and shut everything and keep the heat in.

I: Do you ever notice the cold affect your health, like respiratory problems, or, well, you mentioned circulatory earlier?

J: Well, my asthma is chronic, so I can't say that I notice, but I do feel personally that as I get older obviously my lung function deteriorates and the cold do exacerbate it, but I manage. I hardly have to go to the doctor, I go once a year. They normally say my lung function has gone down a bit, but then, you know, I am 73, I do ballet, I do yoga, I do all kinds of exercice. I am self-helped, I do try to keep myself healthy. I'm sensible.

I: Do you find the damp in here affects your health too?

J: This year, I bought myself a dehumidifier, I find the bedroom is the worst. The clothes I have get damp, so I put it in the bedroom at the moment, and in the daytime I put it in the living room. I find that it does help, I can breathe better with it.

I: How about circulatory problems, you mentioned the Raynaud's, does the cold flare it up?

J: I think this year it is very cold, you can't control it, you stand at the bus stop and the next thing you know your hands and feet are freezing and you can't move.

I: In the house is it ok.

J: Well, it's fine, but I have occasionally dropped my teacup to make tea, because the kitchen is freezing and the heat against my hands means they don't work so well. Because I like to have a cup of tea in bed, and I have dropped the cup a few times. Your hands sort of seize up because there's no feeling, and then they go blue. It comes on suddenly, you have no control over it.

I: If you were feeling cold in the house would you choose to turn up the heating or put on another jumper?

J: I put an extra jumper on and I do exercise, I do all kind of things and I jump about.

I: Is that something you've done all your life? Are you conscious of spending the money?

J: Yes, I never had the money. My husband left me and I brought up two kids, I've been struggling all my life. Nowadays, I just feel it's totally unnecessary, you can keep yourself warm without the heating. Like now if I felt cold, I wouldn't put the heating on, I would just pick up the hoover and start hoovering around or move furniture or dance. If it's a lovely day I will put my walking boots on and go for a brisk walk around the park and come home and then I will have my hot soup and then I don't feel the cold so much.

I: Is that your strategy to cope with the cold?

J: Once a week I will go to the library and sit in there for 4 hours and read through all the papers and books.

I: You've sort of addressed this, but how much do you use extra sources of heat? Like blankets, hot water bottles? You seem to have a lot of strategies to deal with the cold like exercising.

J: Yeah, and also nowadays, I don't drink a lot of coffee and tea, I tend to drink water with lemon and honey as I feel it's more healthy. Or plain hot water.

I: How willing would you be to take up new technologies, like PV panels on the roof, to reduce energy consumption?

J: Well, for it you need the financial resources, which is something I don't have.

I: If there were grants, would you be more inclined to do it?

J: I would, but being in the Grade II list, you can't do anything like that can you.

I: If they did bring in anything like that, which enabled you to reduce energy consumption, so it made it cheaper for you to run the house, would you choose to spend the same amount of money as you are now and get a higher temperature, or would you save the money.

J: Oh yeah, I am conscious of the fact that obviously I'm getting older and at some stage I'm not going to be so active, so obviously I'll need to keep the house at a higher temperature so I don't get hyperthermia. At the moment I know I won't because I'm sensible, but once you're brains gone, well, I have thought about that. My children actually say to me that I need to move into sheltered housing. The trouble is people don't perceive me as being as old as I am, because I'm quite agile, and it's very frustrating, because you always have to keep telling people. Like when you go for concessions, and they look at you funny, so you bring out the bus pass and you say I am 73. I quite resent that. Because I have got grey hair! So you know that is one thing, I know people say it's a blessing because you don't look old, but I would like to be perceived as my age. Like when an old person gets on the bus, I feel obliged to move and the school children don't get up, because I feel that people will look at me and think I should move.

I: In the very cold weather, like when it snows, how do you manage?

J: If I need to go out, like on Sunday I needed to take communion to the sick. So obviously it was my conscience, I have to make an educated judgement between my obligation to the sick people, but if I walk all the way to Oldfield Park, if I fall and I hurt myself it's going to do more harm because I'm going to impinge on NHS and it's not right. So I decided to stay at home. So when I stay at home I get my hot water bottle and I go to bed and I read or write my diary. I keep myself busy and I get up and jump about a bit.

I: So you do manage?

J: Oh yeah, I don't get lonely or not know what to do with myself. I do consciously sort of mind my own well being. But I do get fed up with wrapping myself in blankets because the one I have is a very long one and I often trip over it, I have to be so careful.

I: So you tend to stay in bed for long periods, don't you, that's how you manage?

J: Yeah, and with hot water bottle and hot drinks.

I: Are there any other things that worry you when it gets particularly cold?

J: Not really, I suppose in a way, because I do visit sick people, and I feel a guilt complex in a way, even though I shouldn't. Because my welfare does need to come first. Being of a strong faith I feel I've got to go to Church on Sunday. But other than that no, because the technology is there, you've got email and you can talk to friends and family, you know, so you're not cut off. It's just up to you to know how to manage it. I do have a good network of support.

I: How about things like paying for heating?

J: I manage, I only pay about £40 a month for gas and electricity, but then I only cook one hot meal a day and then when I boil hot water I always put it in a thermos flask, so I can drink that without warming up the kettle again, so I am quite sensible. Then with the hot water bottle from the night before, I use it, I don't empty it until after I've finished breakfast and then I use it to do the washing up.

I: Have you got any other strategies like that?

J: Um, not really, but it's just if I'm cold I do work, I run round and that tends to keep you warm, because there's no point sitting there thinking oh I'm freezing cold and I'll put more blankets on, because your circulation is not going is it. Vascular exercise is important, got to get your blood circulating. It's the best strategy to me anyway.

I: You mentioned the warm front scheme before the interview, does any of that worry you, about being on the best tariff?

J: I wasn't worried, but because of the radio programme, Martin Lewis, and he said about it and he said you have to persist, you persist and you say that you want the cheapest option. So I rang the energy company and he said that there is no cheaper scheme for you so you say well I'll consider switching. And then I tell them about my age and health and so he said I'll write down that you have chronic asthma and you've had cancer in the past and as long as the GP can verify this then you can have it £100 cheaper. But I don't go mad. I don't. Because in the daytime I'm out anyway, like today I'm visiting a retirement home with people in. Then when I get back I'll cook a meal and stay in the kitchen because it's warm, and then I'll get a hot drink and go into the other room, and maybe put the heating on for 2h, from 7pm – 9pm then it will stay a bearable temperature for another hour, and then I will go to bed after the 10pm news.

I: So you've got strategies to manage.

J: Yeah, I like to think I'm quite sensible. And I can, I'm not sure it's my nature, I'm quite resilient, I tend to just plough on and get on with it instead of moan and groan about it. I just think well if I'm cold I've got to do something about it to keep warm, it's no good if I moan to you or my friends, because they can't do anything about it. If you haven't got enough money you just see what you can come up with, buy out of date food, if you've got no money for clothes go to the jumble sale. You know. So I feel that I'm quite sensible. But I mean, I know my house is a bit crappy, but I don't look like somebody in need of help, I manage.

SUSAN:

I: Are you comfortable with the internal temperature in your home?

S: Yes

I: And what do you do to feel comfortable, things like blankets, hot water bottles?

S: Slippers, or a blanket if I fall asleep, if there's a sudden drop in temps I put the heating up, but generally yes I put on another jacket or sweater or blanket and I go to sleep like that.

I: So do you manage. Do you feel the cold more now than when you were younger?

S: I think I do yes.

I: And what age did you first notice you got a bit colder?

S: Well, I suppose it might be psychological, since my husband died 6 years ago, um, and I've had to work things out myself, you know, I think probably then.

I: Do you ever notice the cold affect your health?

S: No, not yet, no.

I: And if you were feeling cold would you choose to put on an extra jumper or turn up the heating?

S: Well, I'd put the jumper on first, then decide, because it varies so much because it can get hot and then it can get cold again.

I: Is it ever due to habit, or what you've done for years, or conscious of the cost?

S: I think so, yeah, if I'm honest I would think about the cost of putting it up when all I have to do is put a sweater on. I would.

I: How much do you use extra sources of heat? Do you use fires?

S: I put the fire on in the sitting room in really cold weather in the evenings and the heating goes down a bit and then I've got the room to myself with the extra fire on.

I: And how willing would you be to take up new technologies, so things like PV panels on the roof?

S: Well, I wouldn't now, not at my age. We're too old now, to see the results and the economics of it. Because my house, particularly facing south, would be perfect but I keep my house nice and warm and I don't find it excessively expensive so you know, I wouldn't go in for that personally, but I think younger people should. Definitely. We've tried to do what they suggest, we've had our walls insulated and the roof. We've done all we can. After I've had my meal at night my heating goes on, I do it manually, and then I put the fire on so I'm nice and cosy and I don't particularly like a hot bedroom but the heat's gone round the house and I'm fine.

I: So the next bit is about energy bills, do you tend to switch or keep the same energy company for long periods and why is that?

S: Ok well, when my husband was alive he did all of that side of it and we were with British Gas and he didn't want to do anything, he didn't want to hear about it. He didn't like the idea of changing it, so when he passed away I listed to the radio and Martin Lewis, and I thought I really ought to do something about that and I was inquisitive and I phoned up and I found that they were £30 more a month. I thought I don't believe it, that can't be right, because we can't believe it, because us older people can't believe that other people will do this to us, and so it's a shock. You know, we expect them to give us a fair deal. I mean I've been with British Gas for a long time and I don't want to change because I don't want the hassle, basically. If I want to keep warm I'm going to have to pay and I cant see that there can be a huge difference and if I want comfort I need to pay a bit extra but I can't think that British Gas can be too much. But if you could get the Government to say that anyone over the age of 75 is going to be on the same electric tariff and the same gas, whoever they're with, that would be absolutely brilliant. But it's just a hassle to have to think 'oh no, I've got to get on the phone again, and their systems change and you can't remember what you do and you just panic.'

I: It's interesting because, fortunately for you, your in a financial position where you can afford to do that and it doesn't have a detrimental impact on anything else but if your someone who's not got that means, it becomes a real problem, because they have these battles with energy providers and it must be, you know, very difficult.

S: Oh it must be awful for people that can't afford it. I am the prime example of someone who doesn't change because they don't want the hassle.

I: And we were saying also about the peace of mind, if there was something that could be offered to older people, all the same.

S: Well, that would be wonderful, say we all reached 75 and all the authorities know that, they could say right well, your energy can come from any of the companies and it's upto them to battle who's going to win that one, and your gas and electric were going to be a certain price that would be wonderful for people. But to be honest, wouldn't it be better if we all had reasonable energy costs so we didn't have terrible worries about it, er, because there's families, I mean there's enough stress in families now without having to worry about having to phone up about an energy bill, for goodness sake. I know lots of people my age, obviously, and they, if they were here now they'd be saying exactly the same, that it causes them more anguish getting on the phone every couple of years and getting the contract sorted and what have you, it causes more hassle. I'm not talking about people who are stupid, we're talking about intelligent people who, you know are very efficient etc, it's not that they're silly, it's just the thought of the hassle of getting on the phone and then you wait and then is it 1 or 2. And then they throw in jargon that you don't understand.

I: Do you think that they might worry that they don't understand it as much as the person on the other end of the phone?

S: Yes, of course, absolutely. They feel a bit inferior, definitely. Definitely, we don't feel as secure as we were years ago.

I: I suppose that it's also if you're not used to it, you know, for my age group we've grown up using computers and iPads, so it's a natural evolution for us to move into that type of thing, but if you're not used to it it must add an extra element of worry when you think 'ok well I don't know how to use this computer and then I've got to search for someone to contact' and that kind of thing, so that must cause anxiety as well.

S: Absolutely. Well I wouldn't be without my ipad or mobile, so I'm happy with that, but it's not quite as easy as ABC. Which is ok, but if it breaks you've got to put it right and that is hassle for people my age, it's something that younger people can manage. I think in Government it's full of younger people and age 65 isn't something they even envisage let alone getting into your 80s. I mean my grandson would be the first to say Grandma don't worry, I'll be over and sort it. Which is comforting, but not at the time, because if I want something, I want it done today, not next week when I see them, but this is something that probably happens, I think my Mum probably felt the same about me.

I: Sometimes it can be worrying can't it, when you don't know how to fix stuff, you don't know the severity of the problem, so what is probably quite easy to a techy 18 year old is not to an older person.

I: I think that's probably the difference isn't it, when you've grown up with it you've got that slight intuition, you think well you've got a rough idea, but if you haven't and you've got to learn that as well it makes everything even more complicated. That's party again about peace of mind with everything in way.

S: Yes, it is. Maybe we should have some kind of welfare system in each city that will help the aged, particularly for them, I mean, we've got Age Concern here, and if you want your insurance through them they'll help you, they're really good, but they've closed it, but ok, their social hub is open but they've closed the information and the insurance and anything we need help with, they've closed it for economic reasons. So what I'm saying is we need a hub of people like that who we could key into without feeling embarrassed and going there and saying look this has happened how should I deal with it, a bit like CAB, but for the elderly. I mean Sirrona is an organisation that calls on you after you're 80, and they came in and asked all different questions, I think they came last year, um she asked me all sensible things, took one look at the house and saw I was managing, so really and truly they could take up the mantle of asking how are you managing energy bills. Yes, where are these people. Infact I did go to age concern to say have we got a Minister fot the Aged? And this lovely lady came out of the social side and said do you know, I don't think we do, no we haven't, so then I told her about what I felt about the energy bills and plan to write to the local MP, and she said write to him, I think you should. Because I think there is a need. But they closed the only office that could possibly have helped.

Appendix 6 - Initial Questionnaire

The HAPIE Project

Health and the ageing population's internal environment

This survey will ask about your household, your home and your attitudes.

The person who completes this survey must be over the age of 65. The survey is confidential and anonymous, meaning your responses will never been seen by anyone else but the researchers and they will not connect your responses with your name or address. You have the choice not to answer any questions you do not wish to and you can end the study at any point.

Section One: About you, your house and your household

1. How old are you?

2. What is your gender?

Male	Female
□	□

3. Please tick the highest qualification you hold.

□ GCSEs, O levels, CSEs, NVQ1, Standard grades (Scotland), or similar

□ A levels, AS levels, NVQ 2 or 3, Highers / Advanced Highers (Scotland), or similar

□ Degree level qualification, including BA, BSc, PGCE, HND, NVQ 4 or 5, or similar

□ Post graduate qualification including Master's degree, doctorate or similar

□ Professional / work related qualifications

□ None of the above

4. What is/was your job?

5. The person who is filling out this form is person 1. Please give some information about the other people in the home.

Person 2

Age (in [ ] years)

Male ☐ Female

Relation to person 1:

Husband, Wife or Partner

☐ Child or Step-child

☐ Parent

☐ Grandchild

☐ Grandparent

☐ Unrelated

Person 3

Age (in [ ] years)

Male ☐ Female

Relation to person 1:

Husband, Wife or Partner

☐ Child or Step-child

☐ Parent

☐ Grandchild

☐ Grandparent

☐ Unrelated

Person 4

Age (in [ ] years)

Male ☐ Female

Relation to person 1:

Husband, Wife or Partner

☐ Child or Step-child

☐ Parent

☐ Grandchild

☐ Grandparent

☐ Unrelated

Person 5

Age (in [ ] years)

Male ☐ Female

Relation to person 1:

Husband, Wife or Partner

☐ Child or Step-child

☐ Parent

☐ Grandchild

☐ Grandparent

☐ Unrelated

6. Please tick the option that reflects your total household income from all sources (eg. Pension, benefits, employment, investment or any other source) before tax and other deductions.

Less than £6000	☐
£6000 - £13,000	☐
£13,000 - £19,000	☐
£19,000 - £26,000	☐
£26,000 - £32,000	☐
£32,000 - £48,000	☐
£48,000 - £65,000	☐
£65,000 or more	☐

7. Which one of these best describes how well you and your household are keeping up with your energy bills at the moment?

☐ I/We manage very well

☐ I/We manage quite well

☐ I/We just manage

☐ I/We have some difficulties

☐ I/We have severe difficulties

☐ Not applicable

8. On how many days, in the past year, have you had to choose between keeping your house warm or buying food this year or last year?

9. What type of tenure is your house?

Owner occupied	Private rented	Social rented
☐	☐	☐

10. How old is your house?

11. Is it solid or cavity walled?

Solid	Cavity	Don't Know
☐	☐	☐

12. Have any of the following retrofit measures ever been installed?

	Yes	No	Don't Know
Loft insulation	☐	☐	☐
Cavity wall insulation	☐	☐	☐
Solid wall insulation	☐	☐	☐
Double Glazing	☐	☐	☐
Photovoltaic/Solar Panels	☐	☐	☐
Biomass boiler	☐	☐	☐
Air/Ground source heat pump	☐	☐	☐

Section Two: Temperature

13. During warm weather how do you find the temperature in your home?

Much too warm	Too warm	Comfortably Warm	Neither warm nor cool	Comfortably cool	Too cool	Much too cool
☐	☐	☐	☐	☐	☐	☐

14. During cold weather how do you find the temperature in your home?

Much too warm	Too warm	Comfortably Warm	Neither warm nor cool	Comfortably cool	Too cool	Much too cool
☐	☐	☐	☐	☐	☐	☐

15. At the moment how do you find the temperature in your home?

Much too warm	Too warm	Comfortably Warm	Neither warm nor cool	Comfortably cool	Too cool	Much too cool
☐	☐	☐	☐	☐	☐	☐

Section Three: Air Movement

16. In general, how do you find the overall air movement in your house?

Much too draughty	Too draughty	Draughty	Not very draughty	Not draughty	Don't know

17. How frequently do you open the windows in your house?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

18. When you do open the windows, how often is it for the following reasons?

	Never	Rarely	Sometimes	Often	Always
To cool the room down.	☐	☐	☐	☐	☐
To improve air quality.	☐	☐	☐	☐	☐
To create a draught.	☐	☐	☐	☐	☐
To reduce moisture.	☐	☐	☐	☐	☐
To smoke.	☐	☐	☐	☐	☐
Because you are drying clothes.	☐	☐	☐	☐	☐

Section Four: Moisture

19. To what extent do you have damp problems in your home?

None at all	☐	☐	☐	☐	☐	In most rooms

20. To what extent do you have condensation/mould problems in your home?

None at all	☐	☐	☐	☐	☐	In most rooms

Section Five: Heating

21. Do you have central heating? (If no, skip to question 22)

Yes	No
☐	☐

21. a) Is it a gas or electric system?

Gas	Electric
☐	☐

21. b) If electric, what tariff are you on?

21. c) Do you know without looking what temperature your thermostat is set at currently? (Skip this question if you do not have a thermostat).

Yes	No
☐	☐

1

21. d) What temperature is your thermostat set to currently? (please check if you are not sure.)

22. Do you have a pre-payment meter?

Yes	No
☐	☐

23. Please read the list of statements and circle the answer that applies to you.

	Strongly Disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
There are big differences between the temperatures in different rooms in my home.	1	2	3	4	5
I like to keep the same temperature in all the rooms of my home.	1	2	3	4	5
I heat the rooms in my home whether or not they are being used.	1	2	3	4	5
I find it easy to keep my home warm when the heating is on.	1	2	3	4	5
I find my home expensive to heat.	1	2	3	4	5
The doors to rooms inside my home are normally left open.	1	2	3	4	5
My home is draughty.	1	2	3	4	5

24. How do you use your heating system? (Please tick all the options that apply)

☐	It is programmed to switch on and off at specific times of day.
☐	The system is on all year round but the heating comes on only when the room temperature goes below a certain level.
☐	I turn the system on in winter and turn it off in summer, but the heating comes on only when the room temperature goes below a certain level.
☐	I turn it on when I feel cold/when I need to.
☐	Other, please specify:

25. Does the heating in your bedroom come on at the same time as the heating in your living room?

Yes	No
☐	☐

26. What kind of boiler do you have?

Combi	
Conventional	
Don't know	
Other, please specify:	

27. How old is your boiler?

	Years

28. How frequently do you have it serviced?

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29. When you feel cold, how often do you do the following actions?

	Never	Rarely	Sometimes	Often	Always
I use an electric blanket to keep warm at night.	☐	☐	☐	☐	☐
I wear extra clothing.	☐	☐	☐	☐	☐
I eat/drink something hot.	☐	☐	☐	☐	☐
I do some exercise.	☐	☐	☐	☐	☐
I use a hot water bottle.					
I use an extra heater.					
I stay in bed for longer periods.					
I use fewer rooms in the house, closing unused ones.					

30. Do you use any forms of secondary heating? (please tick all the options that are appropriate.)

Gas Fire	
Wood burner/ Open fire	
Electric heaters	
Night storage heaters	
Other, please specify.	

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Section Six

31. Please answer true or false to the following statements.

	True	False
I am the type of person who acts environmentally friendly.	☐	☐
Acting environmentally friendly is an important part of who I am.	☐	☐
We are approaching the limit of the number of people the Earth can support.	☐	☐
Plants and animals have just as much rights as humans to exist.	☐	☐
Humans have the right to modify the natural environment to suit their needs.	☐	☐
Humans are severely abusing the environment.	☐	☐
When humans interfere with nature it often produces disastrous consequences.	☐	☐
Human ingenuity will ensure that we do not make the Earth unlivable.	☐	☐
The Earth has plenty of natural resources if we just learn how to develop them.	☐	☐

Section Seven – Health

As some of these questions are personal, please bear in mind that you do not have to answer any questions you do not wish to.

Well-being

32. Overall, how satisfied are you with your life? (1= very dissatisfied, 7= very satisfied)

1	2	3	4	5	6	7

33. Overall, to what extent do you feel the things you do in your life are worthwhile? (1=not worthwhile, 7= very worthwhile)

1	2	3	4	5	6	7

34. Overall, how is your health in general? (1= very bad, 7= very good)

1	2	3	4	5	6	7

35. Overall, how anxious did you feel yesterday? (1= very anxious, 7= not anxious at all)

1	2	3	4	5	6	7

Adult health status and limitations

36. During the past 12 months approximately how many days did illness keep you in bed more than half of the day (including days while overnight patient in hospital)?

Days	

37. Compared with 12 months ago would you say your health is better, worse, or about the same?

Better	☐
Worse	☐
About the same	☐

38. The next questions ask about difficulties you may have doing certain activities because of a health problem. Please tick how you able you feel to carry out each activity.

	Very difficult	Difficult	Manageable	Easy	Very Easy
Walk quarter of a mile	☐	☐	☐	☐	☐
Walk up 10 steps without resting	☐	☐	☐	☐	☐
Stand or be on your feet for about 2 hours	☐	☐	☐	☐	☐
Sit for about 2 hours	☐	☐	☐	☐	☐
Stoop, bend or kneel	☐	☐	☐	☐	☐
Reach above your head	☐	☐	☐	☐	☐
Carry a bag of groceries	☐	☐	☐	☐	☐
Push or pull large objects like a living room chair	☐	☐	☐	☐	☐
Go out for social activities	☐	☐	☐	☐	☐
Do things to relax at home (reading, watching TV, sewing)	☐	☐	☐	☐	☐

39. Do you suffer from any of the following health complaints?

	Yes	No
Impaired vision	☐	☐
Hearing problems	☐	☐
Arthritis or rheumatism	☐	☐
Cardiovascular/heart problems	☐	☐
Hypertension or high blood pressure	☐	☐
Lung or breathing problems	☐	☐
Neurodegenerative diseases	☐	☐
Depression, anxiety, or an emotional problem	☐	☐
Circulatory problems	☐	☐

40. Do you smoke? (If no, skip to question 37).

Yes	No
☐	☐

40 a. How long have you smoked for?

40 b. How many cigarettes do you smoke a day?

41. Do you drink? (If no, skip to question 38).

Yes	No
☐	☐

41 a. How many units of alcohol do you consume in a week?

Physical Activity

42. Do you do any planned physical activity every week? For example, walking, tennis, swimming, yoga. (If no, skip to question 43).

Yes	No
☐	☐

42. b) If yes, please write in the box below which activities you do.

42. c) How much time do you spend a week doing these activities?

	Minutes

Access to Health Care

43. In the past 12 months have you seen any of the following?

	Yes	No
A psychiatrist, psychologist or social worker	☐	☐
A medical specialist	☐	☐
A general practitioner	☐	☐
An Accident and Emergency Doctor	☐	☐
An inpatients Doctor/Consultant	☐	☐
An outpatients Doctor/Consultant	☐	☐

44. In the past 12 months have you received care at home from a nurse, doctor or other health care professional?

Yes	No
☐	☐

Mental Health

45. In the past month, how often did you feel?

	Very often	Often	Sometimes	Rarely	Never
Sad/Tearful	☐	☐	☐	☐	☐
Happy	☐	☐	☐	☐	☐
Nervous	☐	☐	☐	☐	☐
Confident	☐	☐	☐	☐	☐
Hopeless	☐	☐	☐	☐	☐
Excited	☐	☐	☐	☐	☐
Worthless	☐	☐	☐	☐	☐
Loved	☐	☐	☐	☐	☐
Restless	☐	☐	☐	☐	☐
Content	☐	☐	☐	☐	☐
Unable to cope	☐	☐	☐	☐	☐
Cheerful	☐	☐	☐	☐	☐
Lonely	☐	☐	☐	☐	☐

Section Eight - Clothing

46. What are you currently wearing? Please select the clothing items from the list.

SHIRTS AND JUMPERS	
Short-sleeved shirt	☐
Long-sleeved shirt	☐
T-shirt	☐
Polo shirt	☐
Blouse	☐
Thin Jumper	☐
Thick Jumper	☐
TROUSERS AND SKIRTS	
Shorts	☐
Thin trousers	☐
Thick trousers	☐
Thin skirt	☐
Thick skirt	☐
Dress	☐

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FOOTWEAR	
Thin socks	☐
Thick socks	☐
Bare feet	☐
Tights	☐
Sandals	☐
Shoes	☐
Boots	☐

47. How frequently do you wear this amount of clothing indoors?

Very frequently (approximately 90% of the time)	
Frequently (approximately 75% of the time)	
Sometimes (approximately 50% of the time)	
Rarely (approximately 25% of the time)	
Very rarely (approximately 10% of the time)	

Thank you very much for completing the questionnaire.

Appendix 7 - Monthly Questionnaire

The HAPIE Project

Health and the ageing population's internal environment

The person who completes this survey must be over the age of 65. The survey is confidential, meaning your responses will never been seen by anyone else but the researchers. You have the choice not to answer any questions you do not wish to and you can end the study at any point.

NAME: ………………………………….

DATE: …………………………………..

1. Over the past fortnight have you spent any time away from home?

Never	2-5 nights	6-8 nights	9-14 nights

2. Throughout the day, what time is your heating system set to turn on and switch off?

3. Over the past fortnight how have you found the temperature in your home?

Much too warm	Too warm	Comfortably Warm	Neither warm nor cool	Comfortably cool	Too cool	Much too cool

4. Over the past fortnight how have you found the humidity levels in your home?

Much too humid	Too humid	Comfortably humid	Neither humid nor dry	Comfortably dry	Too dry	Much too dry

5. Over the past fortnight how frequently have you opened the windows?

Never	Rarely	Sometimes	Often	Always

6. Over the past fortnight how often did you participate in sitting activities such as reading, watching TV or doing handcrafts? (If never, skip to Q6)

Never	Seldom (2-5 days)	Sometimes (6-8 days)	Often (9-14 days)

6a. On average, how many hours per day did you do these activities?

Less than 1hour	1-2 hours	2-4 hours	More than 4 hours

6b. How much does the temperature inside your home affect how easily you can do these activities?

Not at all	Not much	Sometimes	All the time

7. Over the past fortnight how often did you leave your house? (For any reason, eg. social activities, shopping, doctor's appointments)

Never	Seldom (2-5 days)	Sometimes (6-8 days)	Often (9-14 days)

8. Over the past fortnight how often did you engage in sport or recreational activities such as walking, swimming, bowling, fishing? (If never, go to Q8)

Never	Seldom (2-5 days)	Sometimes (6-8 days)	Often (9-14 days)

8a. On average, how many hours per day did you engage in these activities?

Less than 1hour	1-2 hours	2-4 hours	More than 4 hours

8b. What were these activities?

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9. Over the past fortnight how often have you done the following actions to keep warm?

	Never	Rarely	Sometimes	Often	Always
I used an electric blanket to keep warm at night.					
I put on extra clothing.					
I used an extra heater.					
I used a hot water bottle.					
I used a blanket.					

10.Over the past fortnight how would you rate your sleep quality?

Very good	Good	Average	Poor	Very poor

11.Over the past fortnight have you seen any of the following?

	Yes	No
A general practitioner		
An Accident and Emergency Doctor		
An inpatients Doctor/Consultant		
An outpatients Doctor/Consultant		

11b) Was the visit it in relation to any of the following problems? (please tick all that apply)

Arthritis or rheumatism	
Lung or breathing problems	
Circulatory problems	
Depression, anxiety or an emotional problem	

Please add any comments you have in the box.

Thank you very much for completing the questionnaire.

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Appendix 8 - Participant Flyers

How does your home affect your health?

Are you:

- Over 65 years old?
- Interested in staying healthy and comfortable in your home?
- Willing to take part in a study measuring internal environment and health?

The Project:

With an ageing population, it's important to ensure people can live comfortably at home for as long as possible. We know that the over 60 demographic is most at risk of the health effects of cold and damp homes, but we don't know much about their internal environment – what internal temperatures are achieved, how comfortable people are in their homes and how much of an impact building efficiency has. This research aims to answer those questions through placing temperature and humidity sensors in homes of people aged over 60 and asking questionnaires.

Contact:

If you would like some more information or would be willing to participate please contact Caroline Hughes by either emailing C.E.Hughes@bath.ac.uk, or writing to Caroline Hughes, Department of Architecture and Civil Engineering, University of Bath, Claverton Down, Bath, BA2 7AY.

Thank you very much for taking the time to read this, I look forward to hearing from you if you're interested.

UNIVERSITY OF BATH

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Are you:

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Participation:

There are two aspects to participating in the study:

1. Allowing three temperature and humidity sensors to be placed in the living room and main bedroom (two in the living room and one in the bedroom). Once they're in place they can be left alone quite happily and won't cause any disruption.

2. Answering one reasonably comprehensive questionnaire at the beginning of the study followed by much shorter fortnightly questionnaires (1 page of A4, tick box style questions). I would either email them over to you, or drop them off and collect them once completed, it depends which you would prefer. Also, if you were to sign up and were away or very busy at any point, it would be absolutely fine to miss answering one or two of the questionnaires, I don't want anyone to feel under any pressure throughout the project.

Both of these aspects contribute to the data collection part of the project, which will be split into three phases. Phase one will run from the end of this month until March 2017, the second will run from May 2017 - September 2017 and the final phase will run from November 2017 - March 2018.

Appendix 9 - Thermal Comfort Models

Fanger's Predicted Mean Vote (PMV) and Percentage of People Dissatisfied (PPD) Model

Fanger's model, created in the 1970s as a tool to assist Heating, Ventilation and Air Conditioning (HVAC) designers in creating spaces that enhanced productivity, remains the most influential and widely used thermal comfort model to date. Through subjecting 1300 working age people and 128 older people to a series of environmental conditions and asking them to vote on their comfort preferences, he deduced six variables that determine thermal comfort (vanHoof and Hensen 2006*a*). The variables include four environmental conditions: air temperature, mean radiant temperature, relative humidity and air velocity, and two personal variables: clothing and metabolic rate. From this the PMV/PPD model was created (Equations for model shown in Appendix 1), providing the first practical method of predicting thermal comfort given either measured or estimated values for the six variables. It was incorporated into British Standards in 1984, where it remains part of BSI EN ISO 7730 (BSI 2005). The PMV output gives a value between -3 and +3 which corresponds with a degree of comfort, shown in Table 3.

Table 3: Bedford Thermal Comfort Scale.

Response	Scale
Much too warm	3
Too warm	2
Comfortably warm	1
Neither warm nor cool	0
Comfortably cool	-1
Too cool	-2
Much too cool	-3

The PPD is a function of PMV intended to show the percentage of people in a given environment that will be dissatisfied, or in other words, uncomfortable, for the PMV output, shown in Equation 5.

$$\mathrm{PPD} = 100 - 95 \cdot \exp(-0.03353\mathrm{PMV}^4 - 0.2179\mathrm{PMV}^2) \tag{5}$$

Figure 3 shows how the PPD is low for PMV's between -0.5 and +0.5 and increases as the thermal environment becomes more extreme. A PMV of between -0.5 and +0.5, which corresponds with a PPD of 10% or less, is considered ideal and is recommended for thermal comfort (BSI 2005).

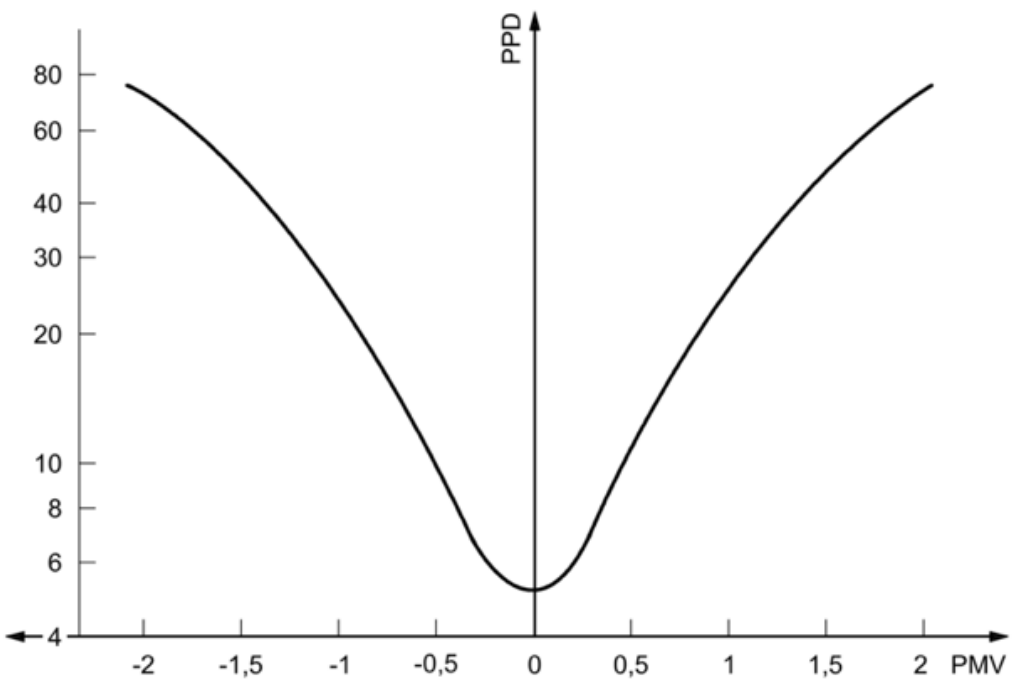

Figure 3: PPD as a function of PMV (ISO 7730, 2005)

Despite its widespread use, Fanger's PMV/PPD model does have flaws (Becker and Paciuk 2009). Critics argue that difficulties arise in assuming the personal variables (Havenith et al. 2008, Luo et al. 2018), inaccuracies result from measurement of the environmental variables (Humphreys and Nicol 2002) and most significantly, the model does not incorporate any ability for human adaptation (Nicol and Roaf 2017). Additionally, it does not take into account culture, climate, season, age, gender, or any psychological factors, such as thermal expectation, all of which are said to affect how people perceive their environment (Parsons 2002, Nicol and Roaf 2017). As a consequence of the problems with the PMV-PPD model's prediction of thermal comfort (Humphreys 1976, de Dear 2004, vanHoof 2008) use of the alternative adaptive model has been increasing (Halawa and vanHoof 2012).

Adpative Thermal Comfort Model

Unlike Fanger's PMV/PPD model, the adaptive model does not prescribe a set of parameters and predict a certain comfort value based on such parameters, but rather recognises that people play a significant part in dictating their own comfort. Hence, the adaptive model provides comfort temperature bands, in which any occupant should be able to achieve comfort given sufficient means to adapt their environment (Nicol and Humphreys 1973). The thought is that in addition to the natural response mechanisms of the body, people will change activity levels or clothing to improve comfort. The adaptive model has been incorporated into both ASHRAE 55 (ASHRAE 2013) and BS EN ISO 15251 (BSI 2007*a*).

ASHRAE Standard 55

The ASHRAE Standard 55 was the first to incorporate an adaptive thermal comfort model, based on work by Brager and DeDear (de Dear and Brager 1997), where over 21,000 buildings in countries worldwide were monitored. Results enabled derivation of the ASHRAE thermal comfort equation, which is said to be suitable for naturally ventilated buildings during summertime, as the model specifies prevailing mean outdoor temperature boundaries of:

$$T_{out} \geq 10C and T_{out} \leq 35C. \quad (6)$$

The model equation is as follows:

$$T_{comf} = 0.31T_{out} + 17.8 \quad (7)$$

Where T_{comf}(°C) is the comfort temperature and T_{out} (°C) is the prevailing mean outdoor temperature. The equation represents a linear relationship between internal comfort temperature and the outdoor air temperature,where the comfort temperature is most affected by the most recent outdoor temperature, so the following equation is frequently used to exponentially weight the running mean outdoor air temperature.

$$T_{rm} = (1 - \alpha)(T_{od-1} + \alpha T_{od-2} + \alpha T_{od-3}...) \quad (8)$$

Where, T_{rm} (°C) is the running mean temperature, the value for α is suggested as 0.8 in CIBSE (2013), although anywhere between 0.6 and 0.9 can be used, and T_{od-1} is the previous day, T_{od-2} is the day before that, and so on.

There are two comfort acceptability categories, discussed in Section 2.1.3, neither of which are suggested for use in homes of the elderly, unlike in the BS EN ISO 15251 standard.

BS EN ISO 15251 Standard

The BS EN ISO 15251 standard is used for buildings in Europe and contains the following equation:

$$T_{comf} = 0.33T_{rm} + 18.8 \quad (9)$$

Where T_{comf}(°C) is the comfort temperature and T_{rm} is the outdoor running mean temperature of the previous 7 days. Figure 4 shows the acceptable temperatures bands of each building category (see section 2.1.2 for description of Category I, II and III buildings).

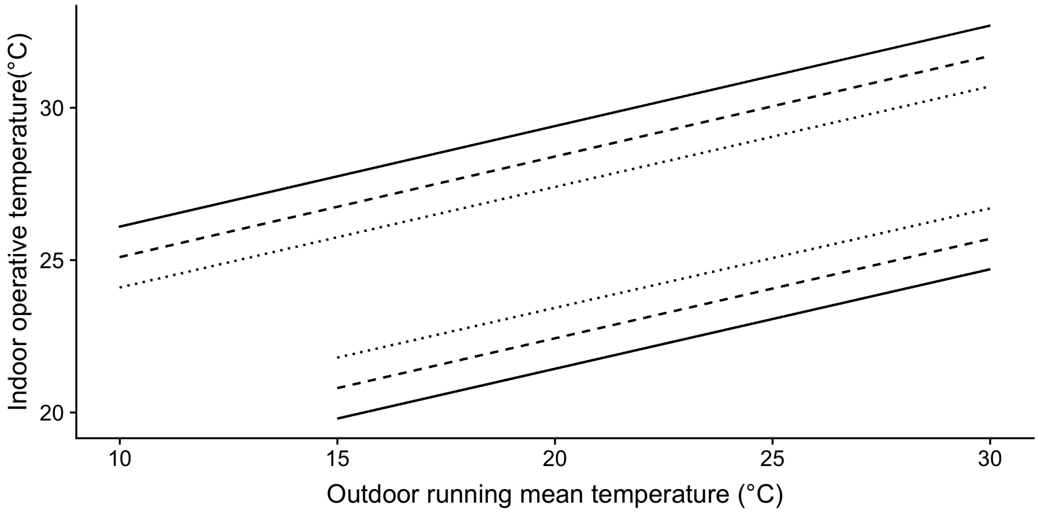

Figure 4: Operative temperature for buildings without mechanical cooling systems, based on BS EN ISO 15251 (BSI 2007*a*). Applies when the upper limit meets $10 < T_{out} < 30$°C and the lower limit meets $15 < T_{out} < 30$°C. Black dotted lines show the upper and lower limits for Category I, black dashed lines show the upper and lower limits for Category II and black solid lines show the upper and lower limits for Category III buildings.

Appendix 10 - Input variable influence to PMV and PPD

Table 4: PMV and PPD outputs for a met rate of 0.8

Air Temperature	Thermal Insulation (Clo)	PMV	PPD
16	0.6	-5.3	100.0
16	0.7	-4.7	100.0
16	0.8	-4.3	99.9
16	0.9	-3.9	99.9
16	1.0	-3.5	99.9
16	1.1	-3.1	99.6
16	1.2	-2.9	98.5
16	1.3	-2.6	95.7
17	0.6	-4.8	100.0
17	0.7	-4.3	99.9
17	0.8	-3.9	99.9
17	0.9	-3.5	99.9
17	1.0	-3.1	99.6
17	1.1	-2.8	98.2

17	1.2	-2.6	94.8
17	1.3	-2.3	89.0
18	0.6	-4.4	99.9
18	0.7	-3.9	99.9
18	0.8	-3.5	99.9
18	0.9	-3.1	99.5
18	1.0	-2.8	97.7
18	1.1	-2.5	93.6
18	1.2	-2.3	86.7
18	1.3	-2.0	77.8
19	0.6	-3.9	99.9
19	0.7	-3.5	99.9
19	0.8	-3.1	99.4
19	0.9	-2.7	97.2
19	1.0	-2.4	92.1
19	1.1	-2.2	83.9
19	1.2	-1.9	73.7
19	1.3	-1.7	62.8
20	0.6	-3.5	99.9
20	0.7	-3.0	99.3
20	0.8	-2.7	96.5
20	0.9	-2.4	90.1
20	1.0	-2.1	80.4
20	1.1	-1.8	68.9
20	1.2	-1.6	57.1
20	1.3	-1.4	46.3
21	0.6	-3.0	99.1
21	0.7	-2.6	95.6

21	0.8	-2.3	87.7
21	0.9	-1.9	76.2
21	1.0	-1.7	63.3
21	1.1	-1.5	50.8
21	1.2	-1.3	39.9
21	1.3	-1.1	30.9
22	0.6	-2.5	94.4
22	0.7	-2.2	84.5
22	0.8	-1.9	71.1
22	0.9	-1.6	56.9
22	1.0	-1.4	44.0
22	1.1	-1.2	33.3
22	1.2	-0.9	24.9
22	1.3	-0.8	18.5
23	0.6	-2.1	80.5
23	0.7	-1.8	64.9
23	0.8	-1.5	49.7
23	0.9	-1.2	36.8
23	1.0	-1.0	26.7
23	1.1	-0.8	19.2
23	1.2	-0.6	13.8
23	1.3	-0.5	10.01
24	0.6	-1.6	57.7
24	0.7	-1.3	41.9
24	0.8	-1.1	29.4
24	0.9	-0.9	20.3
24	1.0	-0.7	14.0
24	1.1	-0.5	9.8

24	1.2	-0.3	7.2
24	1.3	-0.2	5.7

Table 5: PMV and PPD outputs for a met rate of 0.9

Air Temperature	Thermal Insulation (Clo)	PMV	PPD
16	0.6	-4.2	99.9
16	0.7	-3.7	99.9
16	0.8	-3.3	99.8
16	0.9	-2.9	98.7
16	1.0	-2.6	95.5
16	1.1	-2.3	89.3
16	1.2	-2.1	80.5
16	1.3	-1.9	70.1
17	0.6	-3.8	99.9
17	0.7	-3.3	99.9
17	0.8	-2.9	98.8
17	0.9	-2.6	95.3
17	1.0	-2.3	88.4
17	1.1	-2.0	78.6
17	1.2	-1.8	67.4
17	1.3	-1.6	56.2
18	0.6	-3.3	99.9
18	0.7	-3.0	98.9
18	0.8	-2.6	95.1
18	0.9	-2.3	87.4
18	1.0	-2.0	76.6
18	1.1	-1.7	64.4

18	1.2	-1.5	52.5
18	1.3	-1.3	41.9
19	0.6	-2.9	98.9
19	0.7	-2.6	94.9
19	0.8	-2.2	86.3
19	0.9	-1.9	74.3
19	1.0	-1.7	61.0
19	1.1	-1.5	48.5
19	1.2	-1.3	37.7
19	1.3	-1.1	28.9
20	0.6	-2.6	94.8
20	0.7	-2.2	85.1
20	0.8	-1.9	71.6
20	0.9	-1.6	57.3
20	1.0	-1.4	44.2
20	1.1	-1.2	33.4
20	1.2	-0.9	24.9
20	1.3	-0.8	18.4
21	0.6	-2.2	83.7
21	0.7	-1.8	68.6
21	0.8	-1.5	53.1
21	0.9	-1.3	39.6
21	1.0	-1.1	28.9
21	1.1	-0.9	20.8
21	1.2	-0.7	14.9
21	1.3	-0.6	10.9
22	0.6	-1.8	65.1
22	0.7	-1.5	48.4

22	0.8	-1.2	34.7
22	0.9	-0.9	24.3
22	1.0	-0.8	16.9
22	1.1	-0.6	11.8
22	1.2	-0.4	8.4
22	1.3	-0.3	6.4
23	0.6	-1.4	43.4
23	0.7	-1.1	29.6
23	0.8	-0.8	19.8
23	0.9	-0.6	13.2
23	1.0	-0.4	9.0
23	1.1	-0.3	6.5
23	1.2	-0.1	5.3
23	1.3	0.0	5.0
24	0.6	-1.0	24.3
24	0.7	-0.7	15.4
24	0.8	-0.5	9.9
24	0.9	-0.3	6.8
24	1.0	-0.1	5.3
24	1.1	0.0	5.0
24	1.2	0.2	5.5
24	1.3	0.3	6.6

Table 6: PMV and PPD outputs for a met rate of 1.0

Air Temperature	Thermal Insulation (Clo)	PMV	PPD
16	0.6	-3.3	99.8
16	0.7	-2.9	98.3

16	0.8	-2.5	93.5
16	0.9	-2.2	84.6
16	1.0	-1.9	72.9
16	1.1	-1.7	60.3
16	1.2	-1.5	48.5
16	1.3	-1.23	38.2
17	0.6	-2.9	98.7
17	0.7	-2.5	94.1
17	0.8	-2.2	84.8
17	0.9	-1.9	72.2
17	1.0	-1.6	58.8
17	1.1	-1.4	46.3
17	1.2	-1.2	35.8
17	1.3	-1.0	27.2
18	0.6	-2.6	94.8
18	0.7	-2.2	85.1
18	0.8	-1.9	71.5
18	0.9	-1.6	57.1
18	1.0	-1.4	43.9
18	1.1	-1.12	33.1
18	1.2	-0.9	24.6
18	1.3	-0.8	18.2
19	0.6	-2.2	85.5
19	0.7	-1.9	70.8
19	0.8	-1.6	55.3
19	0.9	-1.3	41.5
19	1.0	-1.1	30.4
19	1.1	-0.8	21.9

19	1.2	-0.7	15.8
19	1.3	-0.6	11.4
20	0.6	-1.8	70.1
20	0.7	-1.5	53.3
20	0.8	-1.3	38.8
20	0.9	-1.0	27.5
20	1.0	-0.8	19.2
20	1.1	-0.6	13.5
20	1.2	-0.5	9.6
20	1.3	-0.3	7.1
21	0.6	-1.5	51.1
21	0.7	-1.2	35.9
21	0.8	-0.9	24.4
21	0.9	-0.7	16.5
21	1.0	-0.5	11.2
21	1.1	-0.3	7.9
21	1.2	-0.2	5.9
21	1.3	-0.01	5.1
22	0.6	-1.1	32.8
22	0.7	-0.9	21.4
22	0.8	-0.6	13.9
22	0.9	-0.4	9.2
22	1.0	-0.3	6.5
22	1.1	-0.1	5.3
22	1.2	0.0	5.0
22	1.3	0.2	5.5
23	0.6	-0.8	18.2
23	0.7	-0.5	11.3

23	0.8	-0.3	7.4
23	0.9	-0.2	5.5
23	1.0	0.0	5.0
23	1.1	0.2	5.5
23	1.2	0.3	6.6
23	1.3	0.4	8.3
24	0.6	-0.4	8.9
24	0.7	-0.2	5.9
24	0.8	0.0	5.0
24	0.9	0.1	5.4
24	1.0	0.3	6.7
24	1.1	0.4	8.6
24	1.2	0.5	10.9
24	1.3	0.6	13.5

Table 7: PMV and PPD outputs for a met rate of 1.1

Air Temperature	Thermal Insulation (Clo)	PMV	PPD
16	0.6	-2.7	96.8
16	0.7	-2.3	89.5
16	0.8	-2.0	77.8
16	0.9	-1.7	64.3
16	1.0	-1.5	51.2
16	1.1	-1.3	39.8
16	1.2	-1.1	30.4
16	1.3	-0.9	23.1
17	0.6	-2.4	90.9
17	0.7	-2.0	78.8

17	0.8	-1.7	64.3
17	0.9	-1.5	50.3
17	1.0	-1.3	38.3
17	1.1	-1.1	28.7
17	1.2	-0.9	21.3
17	1.3	-0.7	15.8
18	0.6	-2.1	80.0
18	0.7	-1.8	64.5
18	0.8	-1.5	49.5
18	0.9	-1.2	36.8
18	1.0	-1.0	26.8
18	1.1	-0.8	19.4
18	1.2	-0.7	14.1
18	1.3	-0.5	10.3
19	0.6	-1.8	64.8
19	0.7	-1.5	48.6
19	0.8	-1.2	35.1
19	0.9	-0.9	24.9
19	1.0	-0.8	17.5
19	1.1	-0.6	12.4
19	1.2	-0.4	8.9
19	1.3	-0.3	6.8
20	0.6	-1.4	47.6
20	0.7	-1.2	33.4
20	0.8	-0.9	22.9
20	0.9	-0.7	15.6
20	1.0	-0.5	10.8
20	1.1	-0.4	7.7

20	1.2	-0.2	5.9
20	1.3	-0.1	5.1
21	0.6	-1.1	31.5
21	0.7	-0.9	20.8
21	0.8	-0.6	13.7
21	0.9	-0.4	9.2
21	1.0	-0.3	6.6
21	1.1	-0.1	5.3
21	1.2	0.0	5.0
21	1.3	0.1	5.4
22	0.6	-0.8	18.6
22	0.7	-0.6	11.8
22	0.8	-0.4	7.8
22	0.9	-0.2	5.7
22	1.0	0.0	5.0
22	1.1	0.1	5.2
22	1.2	0.2	6.1
22	1.3	0.3	7.5
23	0.6	-0.5	9.9
23	0.7	-0.3	6.5
23	0.8	-0.1	5.1
23	0.9	0.1	5.1
23	1.0	0.2	5.9
23	1.1	0.3	7.5
23	1.2	0.4	9.4
23	1.3	0.6	11.5
24	0.6	-0.2	5.6
24	0.7	0.1	5.0

24	0.8	0.2	5.8
24	0.9	0.3	7.4
24	1.0	0.5	9.5
24	1.1	0.6	12.1
24	1.2	0.7	14.7
24	1.3	0.8	17.7

Table 8: PMV and PPD outputs for a met rate of 1.2

Air Temperature	Thermal Insulation (Clo)	PMV	PPD
16	0.6	-2.2	86.5
16	0.7	-1.9	72.9
16	0.8	-1.6	58.3
16	0.9	-1.4	44.9
16	1.0	-1.2	33.9
16	1.1	-1.0	25.3
16	1.2	-0.8	18.8
16	1.3	-0.7	14.0
17	0.6	-1.9	74.9
17	0.7	-1.7	59.2
17	0.8	-1.4	44.8
17	0.9	-1.2	33.1
17	1.0	-0.9	24.2
17	1.1	-0.8	17.6
17	1.2	-0.6	12.8
17	1.3	-0.5	9.5
18	0.6	-1.7	60.4
18	0.7	-1.4	44.8

18	0.8	-1.4	32.3
18	0.9	-0.9	22.9
18	1.0	-0.7	16.3
18	1.1	-0.6	11.6
18	1.2	-0.4	8.5
18	1.3	-0.3	6.6
19	0.6	-1.4	44.8
19	0.7	-1.1	31.4
19	0.8	-0.9	21.7
19	0.9	-0.7	14.9
19	1.0	-0.5	10.4
19	1.1	-0.4	7.6
19	1.2	-0.2	5.9
19	1.3	-0.1	5.1
20	0.6	-1.1	30.5
20	0.7	-0.9	20.3
20	0.8	-0.6	13.5
20	0.9	-0.5	9.2
20	1.0	-0.3	6.7
20	1.1	-0.1	5.4
20	1.2	0.0	5.0
20	1.3	0.1	5.2
21	0.6	-0.8	18.9
21	0.7	-0.6	12.1
21	0.8	-0.4	8.1
21	0.9	-0.2	5.9
21	1.0	0.0	5.1
21	1.1	0.1	5.1

21	1.2	0.2	5.8
21	1.3	0.3	6.9
22	0.6	-0.5	10.8
22	0.7	-0.3	7.1
22	0.8	-0.1	5.4
22	0.9	0.0	5.0
22	1.0	0.2	5.5
22	1.1	0.3	6.7
22	1.2	0.4	8.2
22	1.3	0.5	10.1
23	0.6	-0.2	6.2
23	0.7	0.0	5.0
23	0.8	0.1	5.3
23	0.9	0.3	6.3
23	1.0	0.4	8.1
23	1.1	0.5	10.2
23	1.2	0.6	12.5
23	1.3	0.7	14.9
24	0.6	0.0	5.1
24	0.7	0.2	6.0
24	0.8	0.4	7.8
24	0.9	0.5	10.2
24	1.0	0.6	12.8
24	1.1	0.7	15.7
24	1.2	0.8	18.6
24	1.3	0.9	21.5

Table 9: PMV and PPD outputs for a met rate of 1.3

Air Temperature	Thermal Insulation (Clo)	PMV	PPD
16	0.6	-1.9	70.6
16	0.7	-1.6	54.9
16	0.8	-1.3	41.2
16	0.9	-1.1	30.4
16	1.0	-0.9	22.2
16	1.1	-0.7	16.2
16	1.2	-0.6	11.9
16	1.3	-0.4	8.9
17	0.6	-1.6	56.8
17	0.7	-1.3	41.9
17	0.8	-1.1	30.1
17	0.9	-0.9	21.5
17	1.0	-0.7	15.3
17	1.1	-0.5	11.0
17	1.2	-0.4	8.2
17	1.3	-0.3	6.4
18	0.6	-1.3	42.7
18	0.7	-1.1	29.9
18	0.8	-0.8	20.8
18	0.9	-0.7	14.4
18	1.0	-0.5	10.2
18	1.1	-0.3	7.5
18	1.2	-0.2	5.9
18	1.3	-0.1	5.2

19	0.6	-1.1	29.8
19	0.7	-0.8	20.0
19	0.8	-0.6	13.5
19	0.9	-0.5	9.3
19	1.0	-0.3	6.8
19	1.1	-0.2	5.5
19	1.2	0.0	5.0
19	1.3	0.1	5.2
20	0.6	-0.8	19.3
20	0.7	-0.6	12.5
20	0.8	-0.4	8.4
20	0.9	-0.2	6.2
20	1.0	-0.1	5.2
20	1.1	0.0	5.0
20	1.2	0.2	5.5
20	1.3	0.3	6.4
21	0.6	-0.6	11.6
21	0.7	-0.3	7.6
21	0.8	-0.2	5.7
21	0.9	0.0	5.0
21	1.0	0.1	5.3
21	1.1	0.2	6.1
21	1.2	0.3	7.4
21	1.3	0.4	9.0
22	0.6	-0.3	6.8
22	0.7	-0.1	5.2
22	0.8	0.1	5.1
22	0.9	0.2	5.8

22	1.0	0.3	7.1
22	1.1	0.4	8.8
22	1.2	0.5	10.8
22	1.3	0.6	13.0
23	0.6	0.0	5.0
23	0.7	0.1	5.3
23	0.8	0.3	6.7
23	0.9	0.4	8.5
23	1.0	0.5	10.7
23	1.1	0.6	13.2
23	1.2	0.7	15.7
23	1.3	0.8	18.3
24	0.6	0.2	6.1
24	0.7	0.4	8.1
24	0.8	0.5	10.5
24	0.9	0.6	13.3
24	1.0	0.7	16.2
24	1.1	0.8	19.2
24	1.2	0.9	22.2
24	1.3	0.9	25.1

Table 10: PMV and PPD outputs for a met rate of 1.4

Air Temperature	Thermal Insulation (Clo)	PMV	PPD
16	0.6	-1.6	54.1
16	0.7	-1.3	39.7
16	0.8	-1.1	28.6
16	0.9	-0.9	20.4

16	1.0	-0.7	14.6
16	1.1	-0.5	10.6
16	1.2	-0.4	7.9
16	1.3	-0.2	6.3
17	0.6	-1.3	41.2
17	0.7	-1.1	28.9
17	0.8	-0.8	20.1
17	0.9	-0.7	14.0
17	1.0	-0.5	10.0
17	1.1	-0.3	7.4
17	1.2	-0.2	5.9
17	1.3	-0.1	5.1
18	0.6	-1.1	29.4
18	0.7	-0.8	19.9
18	0.8	-0.6	13.5
18	0.9	-0.4	9.3
18	1.0	-0.3	6.8
18	1.1	-0.2	5.6
18	1.2	0.0	5.0
18	1.3	0.1	5.1
19	0.6	-0.8	19.7
19	0.7	-0.6	12.9
19	0.8	-0.4	8.8
19	0.9	-0.3	6.4
19	1.0	-0.1	5.3
19	1.1	0.0	5.0
19	1.2	0.1	5.3
19	1.3	0.2	6.1

20	0.6	-0.6	12.3
20	0.7	-0.4	8.1
20	0.8	-0.2	5.9
20	0.9	-0.1	5.1
20	1.0	0.1	5.1
20	1.1	0.2	5.8
20	1.2	0.3	6.9
20	1.3	0.4	8.3
21	0.6	-0.3	7.5
21	0.7	-0.2	5.5
21	0.8	0.0	5.0
21	0.9	-0.1	5.4
21	1.0	0.3	6.4
21	1.1	0.4	7.9
21	1.2	0.4	9.6
21	1.3	0.6	11.6
22	0.6	-0.1	5.2
22	0.7	0.1	5.1
22	0.8	0.2	5.9
22	0.9	0.3	7.4
22	1.0	0.5	9.3
22	1.1	0.56	11.4
22	1.2	0.7	13.6
22	1.3	0.7	16.0
23	0.6	0.2	5.4
23	0.7	0.3	6.8
23	0.8	0.4	8.8
23	0.9	0.5	11.1

23	1.0	0.6	13.7
23	1.1	0.7	16.3
23	1.2	0.8	18.99
23	1.3	0.8	21.6
24	0.6	0.4	8.0
24	0.7	0.5	10.6
24	0.8	0.6	13.5
24	0.9	0.7	16.6
24	1.0	0.8	19.6
24	1.1	0.9	22.7
24	1.2	0.9	25.6
24	1.3	1.1	28.4

Appendix 11 - PMV_e Model residuals

The plot below shows that the residuals for PMV and PMV_e against TSV are homoscedastic.

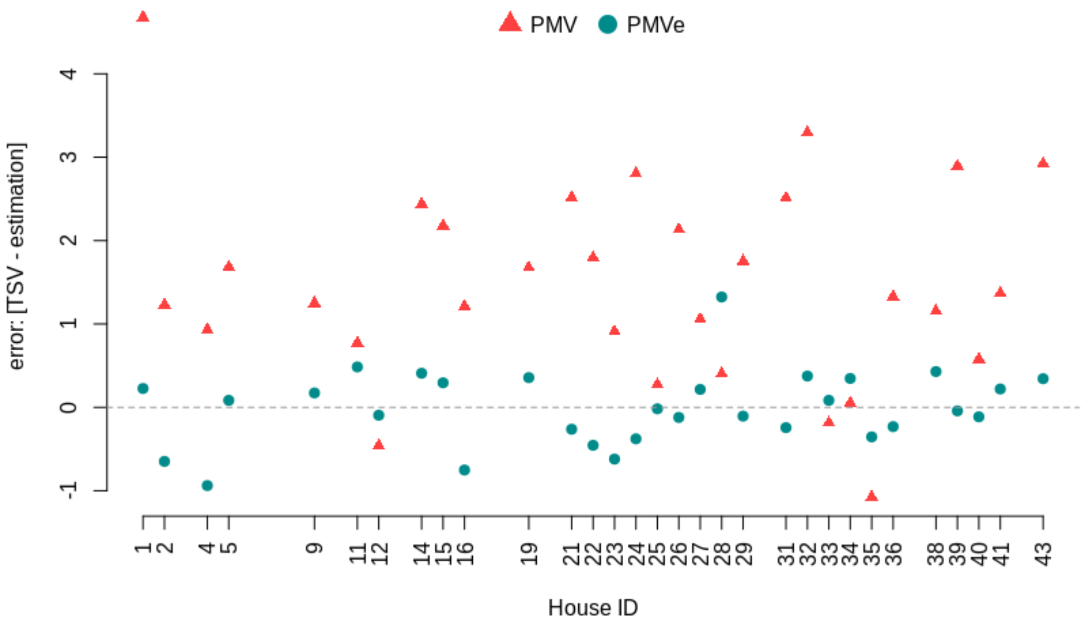

Figure 5: Residuals for the classical PMV model and our new PMV_e model.