Programme Area: Smart Systems and Heat

Project: Comfort Literature Review

Title: Literature Review Findings Report

Abstract:

This report was commissioned by the Energy Technologies Institute to enhance the understanding of the published research in the area of thermal comfort in the homes and includes research into:

- Thermoregulation – deals with temperature changes in the environment and how the complex physiological system maintains body temperature.
- Defining thermal comfort – review on the thermal environment people find comfortable and how age, gender, race and other factors affect the thermal comfort of the individuals.
- Perception of thermal comfort and control – how people perceive thermal comfort and how much control they have to alter their comfort.
- Different models of thermal comfort – Fanger's Model and the Adaptive Model
- Conclusion on the findings.

The findings in the report are critical to developing heating solutions and controls such as Home Energy Management Systems (HEMs).

Context:

The aim of the project is to detail a Home Energy Management System (HEMS) performance specification from the published evidence on comfort and control e.g. definition of the physical parameters that need to be delivered by the HEMS system, for various market segments. The project will summarise the findings and communicate the key implications for the design of better HEMS. Although there are a number of literature reviews of the physiological and psychological factors that influence human comfort, there has been no attempt to date to identify the implications for HEMS design. This work will review the existing literature with a final report summarising implications for HEMS performance. Findings from this work will be used to inform the performance specification of future SSH HEMS systems and to benchmark existing commercial designs.

Domestic Thermal Comfort – Literature Review

D2b: Findings Report

Revision A – 30/04/2014

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1 Introduction

This report forms Deliverable D2b and was commissioned by the Energy Technologies Institute to enhance their understanding of the published research in the area of domestic thermal comfort and the implications for Home Energy Management Systems (HEMS). A review of the literature has been undertaken to identify relevant evidence in the field of domestic thermal comfort and communicate the key implications for HEMS design (see proposal 7161). Following an initial mapping of the area and interviews with experts in the field from Loughborough University, a scoping document was produced and revised (Deliverable D1b) on 21 March 2014. Publications were searched using a range of academic databases and personal collections held by the experts. Search terms were used to assist, but a systematic review was not undertaken. The key aim of the review was to 'to understand thermal comfort in the home, how it can be controlled and the implications for HEMS design'. As such, only those papers that provided information that might specifically relate to HEMS have been reviewed and reported in this document.

A summary of the key findings from the literature is presented in the following sections. In many cases, there is limited information relating to thermal comfort and the domestic environment and much of the research is based on small sample sizes or very specific factors. This makes it difficult to draw definitive conclusions from the literature, and there are many areas where there is very limited information.

The implications for HEMS have been drawn from the available literature by the core project team. These are presented after the review of the literature. A full set of references is also provided, which is supported by a separate Excel file with links to the publications (Deliverable D2a).

2 Defining Thermoregulation

One of the key concepts within thermal comfort is the body's ability to deal with temperature changes in its environment. In this section the complex physiological system that maintains body temperature is described.

Body temperature can be divided into two conceptual parts; the 'core' and the 'shell'. Core temperature has no specific definition, however is generally considered to be made up of the deep internal tissues and vital organs including the heart, liver and brain (Parsons, 2002a). It remains almost constant with slight variations around 37°C depending on the time of day and activity. Studies have shown that in the morning mean core temperatures will be approximately 36.7°C, increasing by around 0.8°C by early evening, and then declining to base levels during the night (Havenith, 2005). By contrast, the 'shell' or skin temperature varies considerably depending on the activity of the body and its surroundings (Guyton & Hall, 2000). It can be localised, with skin temperatures on the extremities, such as fingers or toes, considerably different to those on the chest or forehead, thus making average skin temperatures difficult to measure (Parsons, 2002a).

The body regulates temperature by balancing heat production against heat loss. The body converts energy from calories into useful forms of energy for body function and activity using oxygen (Race, 2006); this varies depending on the metabolic rate. Heat production is a leading by-product of the metabolic process (Guyton & Hall, 2000). The main factors that influence the metabolic rate are body size, age, time of day, environmental temperature, food intake and thermal insulation (Stainer et al., 1984). Our bodies, therefore, produce heat all of the time. The average production rate during sleep is approximately 60 watts, increasing to 140 watts during normal office work and up to 250 watts or more for physical activity such as the exercise (Race, 2006).

In order to be comfortable, there needs to be a balance between heat loss and heat production. If heat loss is greater than heat production, we feel cold. If we cannot release heat quickly enough, we feel hot. This balancing process is called thermoregulation. There are two forms of human thermoregulation; physiological and behavioural.

2.1 Physiological Regulation

Physiological temperature regulation refers to the body's automatic mechanisms to maintain the core temperature around a set point of approximately 37.1°C (Guyton & Hall, 2000). The main control centre for thermoregulation is a part of the brain called the hypothalamus which acts as a thermostatic control for the main organs, but also connects to temperature receptors, predominantly on the skin, but also in the spinal cord and medulla (ibid). These receptors pass information to the hypothalamus control which in turn sends signals to the effectors; the physiological mechanisms to either increase or decrease temperature. When the body is too hot, the temperature is decreased by radiation, convection, conduction and evaporation through the main mechanisms of vasodilation and sweating (Arens & Zhang, 2006; Guyton & Hall, 2000). Vasodilation causes the blood vessels to dilate considerably and transfer heat to the skin, raising skin temperature and thus increasing heat loss (Guyton & Hall, 2000; Parsons, 2002a). When the core temperature rises above 37°C, there is a sharp increase in heat loss via evaporation, predominantly by the production of sweat via the eccrine glands distributed all over the body (Guyton & Hall, 2000; Parsons, 2002a).

When the body temperature drops, the body uses the mechanisms of vasoconstriction, piloerection and shivering to increase temperature. Vasoconstriction restricts heat transfer from the core to the skin. During piloerection the hairs stand on end to try to create a layer of still air between the body and the surroundings (however due to low number of hairs and clothing, this effect is minimal). Finally, shivering, which is an asynchronous contraction of muscle fibres ranging from mild to violent, can increase short term heat production by up to five times (Guyton & Hall, 2000; Parsons, 2002a).

2.2 Behavioural Regulation

Behavioural regulation relates to stimulus from the same thermal receptors as in physiological regulation; however the body responds almost on ‘autopilot’, changing state or environment through learned past experience. “*A simple change in posture, orientation towards a heat source, putting on clothes or movement within the environment can all have significant effects*” (Parsons, 2002, p45). Behavioural control is typically much more powerful in temperature regulation than physiologists have previously stated, and is really the only effective mechanism in extreme temperature environments (Guyton & Hall, 2000).

3 Physiology of Thermoregulation

Understanding how different groups of people respond to hot and cold stress can have a significant impact on their environment and comfort levels. This is a particularly important and evolving area of study to correspond to changes in society. Increasing single occupancy homes, an ageing population, and increasing obesity and other health conditions are all fairly recent demographic developments that affect the way we heat and cool our homes. Thermoregulation in different demographic groups is discussed below.

3.1 The Effect of Ageing on Thermoregulation

How older people respond to changes in temperature is the topic of much debate in both academia and the popular press due to the consequences that extreme temperatures can have. In the UK, older occupants account for 57% of fuel poverty households, whilst estimates suggest there are 40,000 more deaths during the winter months than during the other months of the year, most attributed to older populations (65+) (Wright, 2004). However, despite numerous studies over several decades, the effect of age on thermoregulation is still heavily debated, with no conclusive evidence and conflicting study results.

Some evidence suggests that core body temperatures decrease and become more variable with age. The British National Survey from the early 1970s concludes that as many as 10% of individuals aged 65 and over had early morning temperatures less than 35.5°C (Fox et al., 1973). Conversely, other evidence suggests there is no age effect on core temperatures (Fanger, 1970; Keilson, 1985; Parsons, 2002a). During cold stress, aged skin is associated with a reduced vasoconstrictor response, and loss of active muscle mass accounts for a heat production decrease of 20% between the age of 30 and 70 (Kenney & Munce, 2003). General reports suggest metabolic heat production is lower in older adults, however reports to the contrary do exist (Kenney & Munce, 2003).

During heat stress, several factors have been identified that seem to decline with age, namely a reduction in sweat gland output, skin blood flow, redistribution of blood flow and cardiac output (Kenney & Munce, 2003). Having said that, it is generally considered that there is little temperature difference between fit, healthy older adults and their younger counterparts and that the sedentary lifestyles and deteriorating health conditions of the elderly are considered to have a greater effect on thermal tolerance than age alone (Kenney & Munce, 2003).

Some research has however suggested that health conditions can arise from changes in temperatures and the stress placed upon the thermoregulatory system. Changing between hot and cold rooms can be particularly physiologically stressful, particularly for older people, whilst breathing in cold air can cause loss of lung function and respiratory illness (Wright, 2004).

Part of the reason for the multitude of conflicting studies is the difficulty of disseminating age from other factors affecting thermal tolerance. As well as debate about the weighting to give each temperature reading (base temperature, core, skin, rectal, urine etc), thermoregulation is also affected by a range of medical conditions; menstrual cycle, circadian cycles, general fitness and other factors make a comparison based solely on age extremely difficult. The studies that have shown body temperatures decreasing with age have often not included data such as maximum aerobic capacity – a key determinant of body temperature (Sagawa, Shiraki, Yousef, & Miki, 1988). When this is kept constant and anthropometric and body composition data are consistent, no significant temperature differences are seen between the young and old (Armstrong & Kenney, 1993).

3.2 Gender Differences in Thermoregulation

Gender differences in thermoregulation is another area of considerable debate with conflicting studies amongst academics. Traditional research into the gender differences of thermoregulation have typically revealed there to be little significant differences between males and females, with small variations in comfort level attributed to choice of clothing rather than physiological response (Fanger, 1970; Howell & Kennedy, 1979; Nicol & Humphreys, 2002a). More recent work however, suggests this may not be the case, with significant thermal comfort differences between the genders (Karjalainen, 2012).

A laboratory experiment comparing the responses of 16 male and 16 female participants to changes of temperature along the ASHRAE scale over a 3 hour period in sedentary conditions (watching TV) found no significant differences between genders at slightly warm to warm and slightly cool to cool conditions. However at a PMV value of -2 (cool), females were significantly cooler than males, particularly at the hands (Parsons, 2002b). This is backed up by the considerable systematic review of current evidence into gender differences by Karjalainen (2012) which shows that in both laboratory based and field studies, females express more dissatisfaction with the same indoor environmental conditions than males – specifically in cool environments. Karjalainen's review concludes that:

- Females express more dissatisfaction than males in the same thermal environment, but there are no gender differences at neutral temperature.

- Females are more sensitive to deviations from an optimal thermal condition – especially in cooler conditions.
- Females have more need for individual temperature control and adaptive actions.

It is not entirely clear why females report cooler thermal sensations than males, however it may be due to smaller dimensions of hands/feet, greater sensitivity (physiological & psychological), differences in physiology (averages 20% less body mass, 14% more body fat, 18% less surface area), and reduced blood flow in their hands when exposed to cold (Karjalainen, 2012; Parsons, 2002b).

Studies have shown gender also has an effect on thermal preferences. Interviews with 64 participants showed men were far more likely than women to say they never felt the cold, whilst married couples often reported tensions, with females preferring warmer room temperatures (Wright, 2004).

Having said that, there is considerable evidence to suggest the contrary. In their extensive systematic evidence review on factors influencing thermal comfort comprising of studies from both residential and office buildings from all over the world, Frontczak and Wargocki found both age and gender to have no significant effect on indoor thermal preferences (Frontczak & Wargocki, 2011).

Further studies have shown that the sweating threshold in females is significantly higher (0.3-0.5°C core temperature) than in males and that generally the female thermoregulatory response is at higher temperatures than males (Lopez, Sessler, Walter, Emerick, & Ozaki, 1994). Parsons also notes that the effects of the menstrual cycle on female responses to thermal comfort was found to be insignificant despite the associated changes in internal body core temperature (Parsons, 2002a).

3.3 Circadian Rhythm

The circadian rhythm is the internal daily cycle of physiological processes in living things, often referred to as the ‘body clock’. The circadian cycle is a complex system affected by temperature, metabolism, hormone production and other biological processes in determining thermoregulation, sleeping patterns and food consumption.

Sleep and temperature are two of the key interrelated components of the circadian cycle. Until recently it had been thought that sleep causes circadian changes in thermoregulation, however it has recently been proposed to be the opposite – with rhythmic changes to core body temperatures the cause of time and duration of sleep (Kräuchi, 2007). Studies have shown that sleep is typically induced when core body temperature is at its lowest point during the day, via heat loss at the shell, and waking up occurs when core body temperature starts to rise again (Campbell & Broughton, 1994; Murphy & Campbell, 1997).

To prepare the body for sleep, the core body temperature drops by transferring heat to the shell (skin). This heat loss is coincidentally helped by diverse behavioural actions such as having a warm bath, drinking a hot drink, lying down, or having sex which all induce vasodilation and thus further reduces core body temperatures (Kräuchi, 2007).

3.4 Ethnic differences in Thermoregulation

Research into ethnic differences in thermoregulation is limited and disparate, with a few studies focusing on extreme stress conditions rather than at rest in domestic environments of thermoneutrality. Previous research has suggested that there may be ethnic physiological differences which account for changes in thermoregulation, for example the noted higher blood pressure in African American males compared to Caucasian males (Barnes et al., 2000). Initial research suggests that an increase in metabolic rate to increase core body temperature after cold exposure appears to be attenuated in African American males (Farnell et al., 2008).

Two main theories try to explain physiological differences; the first relates to a different evolutionary path taken and the second is more akin to acclimatisation over a prolonged period of time – where the body adapts to the thermal environment. Whilst studies debating these two theories continue, it should be noted that they concern themselves with the deep understanding of the evolutionary process for various ethnicities at extreme temperatures, which is outside the scope of this review.

3.5 Acclimation and Acclimatisation

Acclimatisation refers to the increase of tolerance to a change in thermal environment after a prolonged exposure. Unlike behavioural adaptation, acclimatisation refers to changes to the body on a physiological level (physiological adaptation). It is typically used to describe exposure in hot environments as studies have proven there to be a physiological change, unlike in cold environments where results regarding a physiological change are inconclusive (Parsons, 2002a). The major physiological change in acclimatisation to hot environments is the ‘training’ of the sweat glands to produce more sweat. In general terms, the more frequent the stimulation of the sweat glands, the more sweat is produced and thus the body is able to efficiently maintain core body temperature (Parsons, 2002a).

Under cold stress it has been hypothesised that the body can acclimatise over time by allowing body temperature to fall, increasing insulation (body fat), or increasing heat production through metabolic rate (Rivolier, Goldsmith, Logg, & Taylor, 1988). However experiments are inconclusive, often due to behavioural adaptations to regain body temperature acting as a bias on the study experiments – and it would seem that behavioural adaptations offer more advantageous temperature regulation than acclimatisation to cold environments (Parsons, 2002a). Humpheys et al agree that whilst there may be some physiological changes to adapt over time, acclimatisation is based on physiological, conscious and unconscious decisions (Nicol, Humphreys, & Roaf, 2012).

Acclimation is artificial acclimatisation and can be induced by making people sweat for more than an hour a day – usually through exercise (Parsons, 2002c). It can be beneficial to train people planning to move to heat stress environments or for performance athletes. Experiments have shown that acclimation to an environment can be improved after five days (although longer is preferable), with sweat rates doubling over this period (Parsons, 2002a).

Despite this, acclimatisation experiments have often been conducted based on exposure to extreme environments (space travel, deep sea diving, mining etc.) and hold little relevance to the everyday work and domestic thermal environment. De Dear and Brager (1998) conclude:

"*On the basis of the majority of experimental evidence published to date, subjective discomfort and thermal acceptability under conditions most typically encountered in residences and office buildings, by resting or lightly active building occupants, appear to be unaffected by the physiological processes of acclimatization"* (de Dear & Brager, 1998, p3).

4 Defining (Thermal) Comfort

Thermal comfort is a complex, multifaceted topic that has been debated by researchers from different schools of thought for decades. Traditionally, technical research has focussed on static models that aim to predict the mean temperatures and thermal balances suitable for human comfort in buildings (Fanger, 1970), whilst more recently research has focussed on the social construct of human behaviour producing adaptive models for thermal comfort (Brager & de Dear, 1998; Nicol & Humphreys, 2002a). In this next section, the key definitions of thermal comfort are presented and the applications and limitations of the current models are explored.

The most widely used and accepted definition of thermal comfort is that of the American Society of Heating, Refrigeration and Air-Conditioning Engineers as *"that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation"* (ASHRAE, 2013). Parsons remarks on the convenience of having such a widely agreed definition that *"emphasises that comfort is a psychological phenomenon, not directly related to physical environment or physiological state"* (Parsons, 2002, p196). Understanding thermal comfort is of paramount importance as it has implications for the way buildings are designed, the way they are heated and cooled and the resulting energy consequences (Brager & de Dear, 1998) and also adds to the overall satisfaction, performance and well-being of the occupants (van Hoof, 2008).

The traditional approach to measuring thermal comfort has been to produce mathematical models that predict people's responses to the thermal environment based on the physiological and psychological reactions of varying thermal conditions (Peeters, de Dear, Hensen, & D'haeseleer, 2009). These heat balance models assess the heat exchange between the body and the environment and ensure that sweat rate and mean skin temperature are within predetermined average comfort levels (Joost van Hoof, Mazej, & Henson, 2010).

The most prominent and applied heat balance model is the Predicted Mean Vote (PMV) developed by Fanger in the late 1960s and published in his seminal book '*Thermal Comfort*' (Fanger, 1970). Using data obtained from climate chamber experiments, Fanger measured sweat rate and skin temperature whilst participants judged their sensation of thermal comfort. The hypothesis for the experiment was that the range of comfort experienced by the participant would be a representation of the physiological strain of the body imposed by the thermal environment (Peeters et al., 2009). His representation of the thermal environment was the combination of six basic parameters of thermal comfort: air temperature, humidity, air velocity, radiant temperature, metabolic rate and clothing.

To calculate thermal comfort using this method, the six parameters need to be measured. The first four; air temperature, humidity, air velocity, and radiant temperature can all be measured on site using specific scientific equipment. Metabolic rate and clothing can be estimated based on databases of average rates for certain demographics, level of exertion and clothing insulation rates for particular garments. Using this research, The ASHRAE 7-point psycho-physical scale was developed to determine a user's level of comfort ranging from -3, cold, through 0, neutral, to +3, hot (ASHRAE, 2013). This allows a method to predict the average comfort level for a large group of individuals within a set of thermal conditions. Fanger, however, recognised that it might be more useful to predict the number of people dissatisfied with the thermal conditions (Peeters et al., 2009). The percentage of people dissatisfied (PPD) shows the unlikeliness of being able to satisfy all people in a large group sharing the same environmental conditions. Whilst complaints about the thermal environment will always exist, it is important to keep them to an absolute minimum. In the PPD, the dissatisfied are those participants that vote outside of the -1 (slightly cool) to +1 (slightly warm) range (Peeters et al., 2009).

The PMV and PPD models have been used extensively in standards relating to thermal comfort throughout building design and engineering. The main international standard for thermal comfort is ISO-7730 which is based on Fanger's PPD and PMV models (ISO, 2005). It also provides a way to assess local discomfort based on draughts, temperature gradients and asymmetric heat radiation (Olesen & Parsons, 2002).

The current standards for thermal comfort are based predominantly on the heat balance model using the original work of Fanger. Fanger's model was adopted so readily as it provides a final 'figure' of thermal comfort that allows designers and engineers to predict the thermal satisfaction of the occupants of an environment. Despite its almost universal use in the standards for thermal comfort over the last 4 decades, the model has come under considerable criticism. Whilst not an exhaustive list, Table 1 below charts the main criticisms to the model, the factors at fault, and the potential errors it may cause.

Table 1: Criticisms of Fanger's model

Criticism	Detail
Solely based on climate chamber data	▪ Experiments were based on steady state lab experiments, predominately with university age students (Brager & de Dear, 1998; Peeters et al., 2009). ▪ Lab experiments imply thermal comfort can be separated and studied independently of other factors (Mcintyre, 1982).

	▪ Artificial lab circumstances are likely to show greater sensitivity to changes in the thermal environment than in normal work/living conditions where people are generally more tolerant to changes in the thermal environment (Howell & Kennedy, 1979).
Sensitivity to estimated and over-simplified clo values and metabolic rates	▪ Clothing insulation treated as a single parameter that could be applied to the whole body (Jones, 2002). ▪ Clothing insulation values differ by as much as 20% depending on the source of the data and the algorithms used to calculate the clo value (Brager & de Dear, 1998). ▪ Clothing values measured under lab conditions with manikins do not account for posture, pumping effect, material fibers, permeability etc (Brager & de Dear, 1998). ▪ No account for the insulation value of chairs and furniture, which can considerably increase clo values (Brager & de Dear, 1998). ▪ Over simplification of metabolic rates based on averages for predetermined activity (van Hoof, 2008). ▪ Experiments were taken with participants in standardised clothing doing sedentary activities (Peeters et al., 2009). In reality, clothing and activity varies in different scenarios.
Does not account for psychological or behavioural adaption	▪ Psychological variables such as whether someone perceives themselves as cold or warm-natured and what they perceive is the current temperature, are key factors not accounted for in Fanger's model (Howell & Kennedy, 1979). There is no incorporation of expectation in the model (van Hoof, 2008). ▪ The model views occupants as a passive recipients of thermal stimuli, unable to adapt or control their comfort level (Brager & de Dear, 1998).
Limited geographical application range	▪ The model is based on experiments in limited geographic locations yet used widely throughout the world (van Hoof, 2008). ▪ Culture and experience have an influence on the description of thermal sensation, not necessarily the sensation itself (Mcintyre, 1982)
Limited to a particular type of building	▪ Predominantly developed for use in air-conditioned offices in temperate zones, the model is now used internationally in both domestic and work environments in passive and actively controlled buildings (Brager & de Dear, 1998; van Hoof, 2008).
Issues with using the 7 point scale	▪ 7 point scale relies on 'neutral' to be the optimum thermal sensation. Studies have shown that people from

	different countries or during different seasons prefer conditions closer to -1 (slightly cool) or +1 (slightly warm) on the scale than neutral (van Hoof, 2008). Therefore results from the model could be biased as they are based on a distorted model of sensation-comfort relations (Howell & Kennedy, 1979). ▪ Studies have shown that the ‘extreme’ range (outside of -1 to +1) on the 7 point scale are actually quite tolerable dependant on other factors e.g. passive cooling etc (Heijs & Stringer, 1988a). ▪ 7 point scale used by Fanger indicates thermal sensation rather than feelings of comfort and changes by participants based on culture and experience (Howell & Kennedy, 1979; Mcintyre, 1982).
Solely accounts for thermal sensation ignoring other comfort factors	▪ Fanger’s model only accounts for human response to thermal conditions. In reality there are a range of factors including demographics, context, environmental interactions and cognition that are key factors in establishing comfort (Brager & de Dear, 1998). ▪ Lighting and acoustics have a higher influence than is often reported (Centnerová, 2010).

As a result of the considerable limitations to Fanger’s model as a complete measure for thermal comfort, several academics have established an alternative adaptive model which moves beyond looking solely at the physiological responses of the body to the thermal environment (Brager & de Dear, 1998; Nicol & Humphreys, 2002a). Rather than simply looking at laboratory based studies, the adaptive model is based on findings ‘in the field’ with participants going about their everyday lives in real world situations (Nicol & Humphreys, 2002a). In the adaptive approach, thermal perception is affected by other factors such as social conditioning, climatic setting, economic considerations and other contextual influences (Brager & de Dear, 1998). The model refers to thermal expectations built up by current and past thermal expectations and cultural and technical norms. A person’s satisfaction with an indoor climate is achieved by matching actual thermal conditions with expectations of what the indoor thermal environment should be like (Brager & de Dear, 1998). The adaptive opportunity is the degree to which people can adapt to their environment and feel satisfied within the space, whilst conversely, when adaptive opportunity is limited, occupants detract from a neutral level of comfort causing stress and dissatisfaction (Baker & Standeven, 1996).

“The adaptive model reflects a ‘give and take’ relationship between the environment and the user, an important premise being that the person is no longer simply a passive recipient of the given thermal

environment…but instead is an active agent interacting with and adjusting to the person-environment system via multiple feedback loops" (Brager & Dear 1998, p85).

There are typically 3 modes of adaptation attributed to this broad definition: behavioural adjustments, physiological adaptation and psychological adaptation.

4.1 Behavioural adjustments

Behavioural adjustments relate to all actions an individual might consciously or unconsciously make to alter their heat balance. Typically, behavioural adjustments are broken down into 3 further sub-categories: reactive, interactive, and cultural (Brager & de Dear, 1998; Nikolopoulou, Baker, & Steemers, 2001). Reactive adjustments relate to changes on a personal level such as changing clothing, posture, activity, location, or even metabolic heat by the consumption of hot or cold food and drink. With interactive adjustment, people change their environment if they have control, such as opening/closing windows or shades, or operating fans, heaters or HVAC systems. Finally cultural adjustments relate to macro activities such as scheduling activities for a particular time of day, adapting dress codes, or altering behaviour patterns e.g. taking siestas.

4.2 Physiological adaptation

Physiological adaptation refers to changes to physiological responses as a result of exposure to thermal environmental conditions. It can typically be divided into two sub categories: genetic adaptation – referring to physiological changes to an individual or a group of people over a long period of time and; acclimation or acclimatisation – changes to the physiological responses in the short term as a result of changes to the thermal environment. Genetic adaptation is not covered within this review, but further details ion acclimatisation was reported in section 3.5.

4.3 Psychological adaptation

Psychological adaptation recognises that past and current thermal experiences can directly affect a person's thermal response and level of satisfaction (Brager & de Dear, 1998). It recognises that all people are different and perceive their environment in a different way. With psychological adaptation, recent thermal history and thermal expectations are important factors that can either influence a person's choice of clothing, affecting their physical thermal sensation, or influence their interpretation of the sensation of dissatisfaction through 'psychological preparation' (Nikolopoulou et al., 2001). Whilst the physical environment is still the most important factor in thermal comfort it would seem that memory and expectations of thermal comfort are a secondary factor in achieving satisfaction with the physical thermal conditions (Nikolopoulou et al., 2001). The majority of research on this subject has been in the non-domestic sector and the full implications for households is still to be explored (K. Vadodaria, Loveday, & Haines, 2014a).

5 Perception of Thermal Comfort

Whilst understanding the underlying physiology of thermoregulation helps to define standards relating to indoor thermal environments, it is also important to accept that various factors will influence occupants' thermal perceptions. In this section the various factors that influence thermal perception are explored and the implications this may have on HEMS design are discussed.

5.1 Temperature Preferences

There are numerous UK based studies that attempt to discover standard household indoor temperatures. Both large scale quantitative studies and smaller scale qualitative research have shown indoor temperatures to peak between 19.1°C to 21.1°C (Oreszczyn, Hong, Ridley, & Wilkinson, 2006; Shipworth et al., 2010; Summerfield et al., 2007). However limitations of the studies include influences of solar heat gain and concentrating on low income or low energy dwellings. Kane et al (2011) monitored the temperature in 292 dwellings in Leicester – the table below shows the average living room temperatures at times of the day by dwelling type (Kane, Firth, Lomas, Allinson, & Irvine, 2011a).

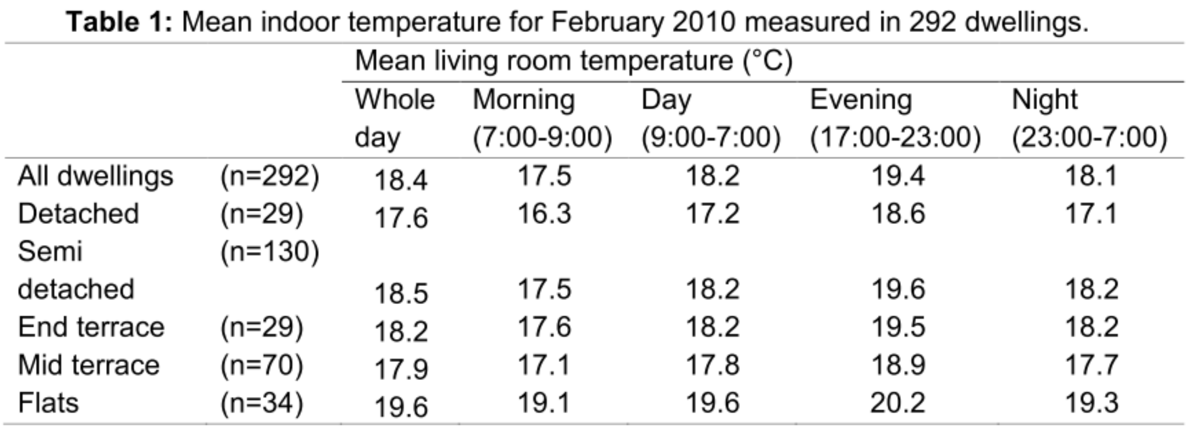


Table 1: Mean indoor temperature for February 2010 measured in 292 dwellings.

		Mean living room temperature (°C)				
		Whole day	Morning (7:00-9:00)	Day (9:00-7:00)	Evening (17:00-23:00)	Night (23:00-7:00)
All dwellings	(n=292)	18.4	17.5	18.2	19.4	18.1
Detached	(n=29)	17.6	16.3	17.2	18.6	17.1
Semi detached	(n=130)	18.5	17.5	18.2	19.6	18.2
End terrace	(n=29)	18.2	17.6	18.2	19.5	18.2
Mid terrace	(n=70)	17.9	17.1	17.8	18.9	17.7
Flats	(n=34)	19.6	19.1	19.6	20.2	19.3

Another area of particularly useful study is the perception of air movement. On some occasions high air movement is seen as a positive factor, however in other situations it is seen as negative and unsatisfactory. Perception of air movement depends on the thermal environment and thermal sensation and personal factors of the occupant (Toftum, 2004). In general, however, in sedentary conditions with temperatures approximately 22-23°C and the occupant feeling neutral or cooler, any air movement may be perceived as negative and unacceptable. In contrast, at temperatures above 23°C with the occupant feeling warmer than neutral or at raised activity levels, occupants do not feel draughts of up to 0.4m/s, typical of indoor environments (Toftum, 2004).

5.2 Age Differences

One of the major influences on the indoor thermal environment is the demographic of the occupants, with a particular influence being age. Interviews with elderly occupants suggest that the thermal environment is often altered as a cause of the increased medical conditions associated with older age. Participants in their 80s also commented on ‘feeling the cold’ more in their later years, thus increasing temperatures (Wright, 2004). Studies have shown that older occupants (65+) prefer warmer living rooms (23.5°C) and cooler bedrooms (21.9°C) than their younger counterparts (22.1° & 22.2°C respectively) (Kane, Firth, Allinson, Irvine, & Lomas, 2010) which corresponds to interviews that suggest older occupants leave their bedroom windows open at night for perceived sleep benefits (Wright, 2004).

Thermal preference also relates to ‘cosiness’ and the feeling of ‘creating a home’. One study with older occupants showed that comfort was not purely a thermal sensation, but had strong cultural values in which visual stimulus (such as the glow from a log fire) was preferred to invisible heat sources (such as underfloor heating) (Devine-Wright, Wrapson, Henshaw, & Guy, 2014a).

Interestingly, studies have shown that elderly occupants heat their homes throughout the year, even during the summer and heat waves because of the preoccupation of being more susceptible to the cold (Lomas & Kane, 2013). This combination of hot outdoor temperatures and heated homes has been labelled a ‘lethal combination’ and Lomas & Kane (2013) suggest health organisations and governments warn occupants with simple information such as turning the heating off during hot periods.

5.3 Perception of Control

Another key factor in an occupant’s satisfaction of the thermal environment is their perceived level of control to alter their conditions. Much of the literature within this field is focused around control in office and work spaces; however useful insights can be drawn from these studies. Occupants are not typically as preoccupied by comfort as discomfort especially in environments that they find it hard to adapt to such as offices (Leaman & Bordass, 2007). They tend to be much more dissatisfied in buildings where they do not understand or do not have control of the thermal environment. That said, whilst having control is seemingly important, evidence suggests having too much control and having to persistently ‘fiddle’ and change settings can be equally frustrating for building occupants (Leaman & Bordass, 2007).

One of the main frustrations from building occupants is the ability to understand information about their thermal environment. Typical terms used in energy management systems such as KWh and m^3

are not understood by regular consumers (Lockton, Bowden, Greene, Brass, & Gheerawo, 2013). Establishing the balance of control and the interface to achieve it is also of upmost importance. Combe et al (2010) found that 66% of occupants of an award-winning low energy housing development could not program their heating controls due to both cognitive and physical interface complexities. Combe et al go on to state that current thermostat design could exclude as much as 30% of the UK population due to difficulties in vision, thinking, dexterity, numeracy and literacy (Combe, Harrison, Dong, Craig, & Gill, 2011). The authors suggest improving both the physical and digital interfaces would help to include more users and reduce energy demand (Combe et al., 2011). Indeed "*Simpler systems with usable controls and interfaces for occupants can give better results in terms of user satisfaction than more elaborate (and often more energy-consuming) systems with control interfaces which are poor in function, location, clarity and responsiveness, or even absent*" (Leaman & Bordass, 2001).

One of the clear messages from the literature in this area is the vast variations in thermal perceptions by building occupants. Comfort expectations are highly malleable and evolving and cannot be defined solely by rigid measurements and numerical values that the static models suggest (Strengers, 2008). The previous static models have informed current standards to such a degree that those parameters have now become normalised in society (Strengers, 2008). Heating and air conditioning systems calculated to current static model factors have changed occupants' thermal expectations to a much narrower range. In reality, occupants are 'satisficers' – happy to tolerate and accept small changes to their thermal environment, providing they perceive they have control (Leaman & Bordass, 2001). In fact, recent research has shown that dynamic thermal environments, which induce moderate physiological changes, can potentially deliver higher levels of occupant satisfaction than static indoor environments (Parkinson, de Dear, & Candido, 2012).

Having said that, by far the majority of studies conducted on thermal perception have been carried out in office and work environments which are vastly different from domestic conditions. *"At home people operate at very different activity levels, with freedom in their choice of clothing, with due consideration for others' thermal state, and in an environment specifically designed to provide abundant adaptive opportunity; they are also concerned about energy costs"* (Lomas & Kane, 2013).

6 Health and Wellbeing

Thermal comfort is intrinsically linked to occupants' health and wellbeing, with various thermal conditions linked to health problems and vice versa. The following section looks at some of the main health conditions affected and caused by different thermal conditions.

6.1 Obesity

Obesity is a serious public health concern that gains almost daily press coverage due to the rapid increase in the last couple of decades. The average weight of an adult in the UK has been increasing by approximately 0.3kg per year since 1993, from 72.4kg to 76.9kg in 2008 (Mavrogianni et al., 2011). Traditional research into the causes of the obesity pandemic has focussed on investigating 'the big two'; reduced physical activity caused by more sedentary lifestyles, and increased intake of 'junk' food caused by marketing and manufacture of high weight gain foods (Keith et al., 2006; Moellering & Smith, 2012). More recently however, some research has suggested there to be a link between indoor thermal environments and the increasing obesity problem.

Like most mammals, humans have a core body temperature that is usually higher than the surrounding ambient temperature. They therefore increase metabolic rate to maintain body temperature (Moellering & Smith, 2012). The thermoneutral zone (TNZ) is the range of ambient temperature in which energy is not required to initiate physiological responses to maintain thermal homeostasis (Keith et al., 2006; Mavrogianni et al., 2011). Increasing time spent in the TNZ and reducing exposure to variations in ambient temperature have been identified as contributors to increased obesity rates (Mavrogianni et al., 2011).

Exact data on indoor temperatures are difficult to compare due to the vast array of different methodologies however evidence suggests a considerable increase in living room temperatures since the 70s (Johnson, Mavrogianni, Ucci, Vidal-Puig, & Wardle, 2011). Reduced exposure to thermal variability due to increased time spent indoors, access to central heating and air conditioning systems, cheap fuel prices and improved energy efficiency of buildings has also contributed to reducing the amount of time the body spends under thermal stress (Mavrogianni et al., 2011).

Laboratory studies have shown there to be an increase in energy expenditure in response to mild cold stress (Mavrogianni et al., 2011) and therefore a reduced exposure to cold stress reduces energy expenditure (Johnson et al., 2011). The lack of variation in thermal stress (particularly seasonally) due to more advanced controls of the indoor thermal environment means there is a reduced ability to regulate energy expenditure (Johnson et al., 2011).

With a non-obese person, a drop in ambient temperature from neutral (22C) to cool (16C) would cause the physiological response of vasoconstriction, increased heart rate, blood flow, fatty acids, insulin and other biological processes. In contrast, due to the insulative properties of excess adipose tissue (fat) the same physiological response is supressed in obese people (Moellering & Smith, 2012).

Studies have however shown that, during cold stress, food intake increases to compensate for increased metabolic rate, a fact utilised by the farming industry to increase weight gain in livestock and the catering industry to increase sales by managing temperature controls (Keith et al., 2006; Moellering & Smith, 2012). However it is unlikely that increased food intake will compensate for total energy loss due to cold exposure, and studies have shown that consumption of appetising and energy dense foods is not typically reduced due to lower energy expenditure (Johnson et al., 2011).

Of course, the link between thermal environments and obesity is hotly debated because of the considerable methodological challenges in conducting a longitudinal study and the vast array of other variables that have to be accounted for. Behavioural adjustments, changes to diet, differing demographics, new technology, sleep patterns and lifestyle changes are just a few other factors that have influenced obesity over the last few decades, and therefore the exact role that the thermal environment plays is difficult to ascertain. It would seem, however, given the above information, that the thermal environment plays an important role in the biological processes of the human body and could contribute to obesity.

6.2 Respiratory Conditions

Further health risks linked to indoor thermal environments are various respiratory conditions. Over the last 25 years the incidence of asthma episodes has increased by a factor of three with the UK having the highest prevalence of asthma symptoms in 13-14 year olds in the world (Howieson et al., 2003). The modern home has often been cited as a major contributor to this, with high thermal insulation to increase energy efficiency often at the detriment of air quality (Shrubsole, Macmillan, Davies, & May, 2014). The main cause of respiratory problems in homes is allergens, with mould more prevalent in damp and humid homes, therefore whilst temperature is important, ventilation and air circulation is the main factor in reducing respiratory problems.

The main causes of respiratory illness in homes are dust mite allergens, pet allergens and mould. Humidity and temperature play a key role in dust mite populations with a narrow band of ideal conditions – a relative humidity of 80% and temperature of 25°C (Howieson et al., 2003). Mattresses and carpets have been described as ‘allergen factories’ – although the prevalence of mite colonies can be reduced by encasing mattresses in allergen protectors (Richardson, Eick, & Jones, 2005). The UK has the highest number of fitted carpets in Western Europe with 98% of homes having carpets compared to just 16% in France and 2% in Italy (Howieson et al., 2003). Studies have shown in the UK that 59% of living room carpet samples, 75% of bedroom carpet samples and 78% of bed surfaces were found to be above the WHO threshold for allergenic sensitisation (Howieson et al., 2003).

Current regulation in the UK, as well as many other countries, is for residential buildings to have a continuous air exchange rate of 0.5 air changes per hour (Richardson et al., 2005); however Howieson et al (2003) indicate that this may not reduce relative humidity below 60% - the threshold for house dust mites. Instead they recommend the use of mechanical heat recovery units to allow ventilation rates of 1.3 air changes per hour to expel moisture and indoor air pollutants without a significant energy cost (Howieson et al., 2003).

Pet allergens are also a common cause of asthma and other respiratory conditions. Cat allergens are by far the most common cause of grievance due to the smaller size of allergen particles (thus easier to inhale). Reduced ventilation and carpeted floors have been known to increase the airborne concentration, however even high extraction rates of 2-3 air changes per hour have a negligible impact due to allergy sufferers detecting allergens at the smallest level (Gore et al., 2003).

Mould is another serious trigger of asthma and other respiratory conditions found to be more severe to allergy sufferers than pet allergens. The most important factors influencing mould growth is relative humidity and temperature. Whilst there are many different types of mould, evidence suggests that at normal indoor temperatures mould growth starts at approximately 75% relative humidity (Clarke et al., 1999). There are few studies however that attempt to understand the significance of mould in indoor environments and the effect on respiratory conditions. Part of the problem is the array of different forms of mould and the difficulty of measuring it, with visible mould already a well formed colony with roots whilst large proportions of mould is ‘invisible’ and airborne (Richardson et al., 2005). Whilst mould can be treated with fungicide, complete eradication requires the removal of conditions for growth, namely: repairing structural problems causing water damage, reducing condensation, and lowering humidity through ventilation.

There is a vast array of global studies into the causes and remedies of respiratory illness, of which the indoor thermal environment is one. However, as with obesity, due to the vast array of variables and difficulties of carrying out accurate longitudinal studies, the exact role the indoor thermal environment has is unclear.

6.3 Sleep

As established in the Physiology section, thermoregulation has a very important role to play in regulating sleep patterns and as such the thermal environment is one of the most important factors affecting sleep.

As previously established, core body temperature drops during sleep (by transferring heat to the skin). Lan et al (2014) conducted a laboratory experiment with healthy Chinese participants that suggested, despite the drop in core temperature, humans prefer warmer than neutral conditions to sleep, but not too warm. In their experiment 23°C was considered too cool, 26°C neutral and 30°C too warm for sleep (Lan, Pan, Lian, Huang, & Lin, 2014). It should be noted however, that bedding was not included during the experiment – a source of considerable comfort and insulation, and studies have shown behavioural thermoregulation as active and considerable during sleep (Okamoto-Mizuno & Mizuno, 2012).

Research into the effect of the thermal environment on sleep is typically focussed on hot conditions, as studies have shown heat stress to cause a greater disturbance on sleep than cold stress. Okamoto-Mizuno (2012) suggests that temperature and humidity in the bed climate (microclimate between the occupant and the bedding) are critical in managing skin temperature for optimal conditions for sleep. During heat stress sleep is disturbed during the initial stages as the ambient temperature and humidity reduce heat loss from the skin, thus supressing the decrease in core temperatures (Okamoto-Mizuno & Mizuno, 2012).

During cold conditions bedding and clothing is generally used to maintain a neutral temperature. One study reported the bed climate remained constant for participants at an average of 30°C whilst the ambient air temperature varied between 16°C to 25°C (Muzet, Libert, & Candas, 1984). Other studies have reported similar results from 3°C to 17°C as it is clear that covers and bedding are used to create an optimum bed climate by behavioural thermoregulation during sleep (Okamoto-Mizuno & Mizuno, 2012). Indeed studies have shown that in hot and humid locations where ambient temperatures are warmer than neutral, air conditioning is used as a behavioural method to reduce ambient air temperature and improve sleep quality (Lan et al., 2014).

Two particularly important groups susceptible to changes in the thermal environment are the elderly and infants. Sleep patterns of elderly people are generally light and intermittent (Kanda, Tochihara, & Ohnaka, 1999). Studies have shown babies to have a developed thermoregulatory cycle by 16 weeks of age (Lodemore, Petersen, & Wailoo, 1991). One study showed parents significantly wrapped their infants (4 months old) adding up to 188% in insulation despite a temperature fall of only 30-40% during the night (Wailoo, Petersen, Whittaker, & Goodenough, 1989). It also suggested parents determine the insulation to give their child based on a random calculation of ambient temperature and weight/size (i.e. vulnerability) of the child, despite evidence of sweating and considerable heat loss through the uninsulated areas (head) (Wailoo et al., 1989).

6.4 Circulation

A further health condition related to the indoor thermal environment is poor circulation. Investigations have shown that having cold extremities and a slightly lower than normal core temperature can lead to increased blood pressure, particularly in elderly people (Collins, 1986). Significant blood pressure rises were observed in elderly subjects at ambient temperatures of 6°C, 9°C, 12°C, but not at 15°C. Considerable seasonal variations between summer and winter were also found in elderly participants in Cambridge, UK and a 1°C decrease in living room temperature was found to be associated with a rise of 1.3mmHg in systolic and 0.6mmHg in diastolic blood pressure (Woodhouse, Khaw, & Plummer, 1993).

The evidence suggests that cardiovascular disease is more prevalent for elderly people during winter, with hospital admissions as high as 70% more than during summer in some temperate European countries (Wilmshurst, 1994).

7 Activities and Behaviour

It has been made clear during the previous chapters that activity level clearly affects an occupant's level of thermal comfort. The type and intensity of activity has a significant effect on thermal comfort as it increases metabolic rate and thus internal body temperatures. One study with 6 young, healthy males found that the same change in ambient temperature was both pleasant and unpleasant depending on the thermal state of the body (Parkinson et al., 2012).

Despite this, data on specific household activities and their precise effects on physiology and perception of comfort are uncommon, predominantly due to the vast array of different activities undertaken and subsequent factors affecting them.

One of the clear difficulties of incorporating activities into any dynamic model of thermal comfort is the fact that everyone is different, with different needs, wants, desires, motivations and abilities. There are so many variables not accounted for in static models such as activity level or recent thermal history for them to be accurate (Hoppe, 2002). The effects of body motion and activity level are too big to be ignored in comfort prediction models, and more accurate or personalised metabolic rate measurements are needed to support more dynamic thermal comfort models (George Havenith & Holme, 2002).

In recent years there has been growing evidence to suggest that home heating is as much to do with the behavioural and social factors of occupants interacting with energy technology as it is to do with the thermal and physical properties of the dwelling (Kelly et al., 2013). Indeed the vast variation in energy consumption in buildings with similar physical characteristics is due to differences in behavioural demands (Guerra-Santin & Itard, 2010). However, it is a relatively new field, with clear gaps in understanding occupancy behaviour and the link to heating demand which need to be explored with further study (Audenaert, Briffaerts, & Engels, 2011). A recent study found that behaviour accounts for 51%, 37% and 11% of the variance in heat, electricity and water consumption respectively across different dwellings (Gill, Tierney, Pegg, & Allan, 2010). As the majority of domestic thermal models do not account for social and behavioural factors they could misrepresent home energy consumption, and in particular heating demand, by as much as ±50% (Kelly et al., 2013).

Occupancy patterns and heating demand may be determined by lifestyle, preferences, attitudes, perceptions of comfort, personal background and household characteristics, and the way people use heating systems is in part determined more by personal factors such as experience, attitude, and origin than by external conditions (Guerra-Santin & Itard, 2010). Indeed household routine and habitual behaviours are important drivers of domestic heating demand. A study by Kelly et al showed that households who had regular weekly heating patterns (usually on timer control) are on average 1.19°C warmer than households with an irregular heating pattern (Kelly et al., 2013). However, households who had different heating patterns over the weekend compared to the working week were on average 0.44°C warmer than homes who kept the same heating pattern for the whole week (Kelly et al., 2013). This is in agreement with evidence that suggests households that have a programmable thermostat generally have warmer temperature settings in the night and radiators on for longer than households without programmable thermostats, although the difference is negligible (Guerra-Santin & Itard, 2010).

Standard heating practice models suggest a daily heating period of 9 hours (2 hours in the morning and 7 hours in the evening), however Kane (2013) found the actual heating period to be 12.6 hours, more than 3 hours longer than standard models. In his study of 249 dwellings in Leicester, Kane found 33% of dwellings were heated for only one period each day, 51% heated their dwellings for two periods each day, 5% heated their dwelling multiple times during the day, and 11% heated their dwelling randomly or without timing (Kane, 2013).

Bathing is an example of an activity in the home that has a multitude of different connotations relating to thermal comfort. Taking a shower for example can be linked to waking up, caring for the body, relaxing, and getting warm (Kuijer, 2011). Activities within the home are very related to cultural norms and traditions (Henning, 2003) and studies have shown bathing to have significantly differing roles in achieving comfort in different cultures (Kuijer, 2011; Wilhite, 1996).

Other studies have shown variations in behaviours related to achieving thermal comfort. During interviews and observations with a very small sample group, Elizondo suggests that the temperature of washing up water is significantly linked to the thermal environment – with some participants in the UK having hot washing up water for the pleasurable feeling of having their hands in warm water to increase their temperature, whilst participants in Mexico suggesting the opposite, using cold water for the pleasant feeling of cooling them down in hot environments (Elizondo, 2011).

With a similarly small sample size, Henning suggests one participant increased their activity level when the temperature was too cold to be sedentary, rather than increase the temperature of the room (Henning, 2003). Rather than regulate room temperature they change activity based on warmer or cooler spaces, for example doing the ironing in the cool basement during summer, or upstairs in a warmer room during winter. Whilst Henning admits this is only anecdotal evidence –

she implies that all people are different and that it is perfectly reasonable to expect people to change activity level or location based on the thermal environment. She suggests designers of HEMS take into consideration opportunities to keep different spaces of the house at different temperatures so occupants can choose the right environment for a particular activity (Henning, 2003).

The existing models and standards which do not put a heavy emphasis on occupancy behaviour can only give a general indication of the state of an occupants' comfort (Gauthier, 2013). Due to comfort assumptions made by current standards that inform the infrastructure and notions of comfort, some authors have suggested that people now expect a narrower temperature band than before as well as rejecting former ways of achieving thermal comfort such as opening a window, bathing, using blankets or appropriate clothing and changing schedules such as having siestas on hot afternoons (Shove, 2003; Strengers, 2008). It is argued that, at a higher level, the relationship between energy providers and consumers and the assumptions within those relationships determine how demand management strategies influence comfort expectations (Strengers, 2008).

8 Physical environment

This section discusses elements associated with the fabric of the home that may have significant influence on thermal comfort.

8.1 Getting thermally comfortable in different environments

8.1.1 Air conditioned buildings compared to naturally ventilated

UK homes are predominantly naturally ventilated. In an extensive review conducted by Brager & Dear (1998) they make a distinction between buildings which are air conditioned and those which are naturally ventilated, with occupants of naturally ventilated building being more comfortable across a greater range of temperatures. A review by Frontczak & Wargocki (2011) make similar findings. Brager and de Dear (1998) argue that occupants of buildings which are air conditioned have different expectations than the occupants of naturally ventilated buildings, suggesting that the occupants of naturally ventilated buildings, not only become more tolerant of the more varied dynamic and non-uniform indoor conditions, but often prefer having a closer connection with the weather and seasonal changes. For occupants of air-conditioned buildings their thermal history comprises of consistent cool, constant and uniform conditions, thus creating more stringent 'comfort criteria' while biasing expectations towards constant HVAC set-points rather than daily or seasonal fluctuations. However Nicol & Humphreys (2002) did not find evidence to support this, commenting that it is more likely that the difference is due to an accumulation of the small effects caused by a wide variety of adaptive actions which together amount to a large difference in conditions for comfort.

8.1.2 Office compared to the home

A literature review conducted by Frontczak & Wargocki (2011) explores how the indoor environment in buildings affects human comfort. In the review they report on two studies which found that people felt warmer at home and colder in the office in relation to the sensation predicted by PMV. Heidari (2002, cited in Frontczak & Wargocki (2011)) in a field study conducted in Iran, showed that the difference in neutral temperature occurred between home and the office environment and a study by (Oseland, 1995) in a field study of UK occupants that compared results from office building, homes of the office workers and a climate chamber, found that thermal sensation differed between home and office environment. However, it was not explored whether the comfort level was different for the two environments.

8.1.3 Hotter UK summer conditions

Adequate heating in homes is the main issue at present, but cooling is likely to become an increasingly important issue over the coming years with rising global temperatures. Therefore, at the same time as improving the energy efficiency of the housing stock, it is essential that cooling needs are taken into account in design, construction and refurbishment to avoid intensive energy demand for cooling in the future (Institute, 2014). A number of research studies have been conducted looking at the effectiveness of interventions to reduce overheating in existing UK homes. These studies used computer modelling techniques to assess different interventions and their effectiveness (Tillson et al. 2013, Porritt et al. 2011, Porritt et al. 2012). Porritt et al found that, of the building types studied, 1960s top-floor flats and 2007 detached houses experience more than twice as much overheating as the other types of homes.

A series of studies have also been conducted looking at the design of windows and their impact on thermal comfort, typically these are also based on computer simulation and modelling techniques. Roetzel, Tsangrassoulis, Dietrich, & Busching, (2010) provide a review of various studies investigating the parameters influencing the effectiveness of occupant controlled natural ventilation primarily looking at facade design and occupant behaviour of window opening. Behaviour and use of windows by occupants in residential context are discussed further in the section ‘Modifying the environment to get comfortable – ventilation’.

8.2 Effect of type of house on thermal comfort

8.2.1 Building type

Research papers regarding thermal comfort in relation to house type are few, however there are a number of research studies regarding house type and room temperatures. Relevant results from these are presented here.

8.2.2 UK housing

Rudge (2012) provides a good overview of the evolution of housing in the UK and its impact on comfort, exploring the historical reasons for the poorly insulated and energy inefficient housing stock in Britain throughout particular eras of building construction. Boardman (1991) cited in Rudge (2012) showed how the British housing stock compared badly with other countries in terms of energy used and the comfort achieved. Boardman highlights that construction methods and quality of workmanship has led to leaky homes in Britain, with the highest rate of air movement being associated with old dwellings.

In a study conducted as part of the CALEBRE project in 2010 in-depth interviews with participants found that occupants of Victorian houses often accepted that their houses would be cold/draughty as a consequence of being older buildings with period features. The occupants' expectations made them more accepting of the thermal conditions provided by these older properties.

Results from a field study looking at UK residential room temperatures, rather than comfort levels, found that house type is related to differences in indoor temperatures, however they found that this relationship was not significant during heated periods (Kane, Firth, Lomas, Allinson, & Irvine, n.d. 2011). In another study by Lomas & Kane (2013) which recorded UK residential room temperatures in the summer, it was found that the results indicated that flats tended to be significantly warmer than other house types. Solid wall homes and detached houses tended to be significantly cooler. Whilst the modelled predictions from Porritt et al (2011, 2012) agree with flats being warmer the information regarding detached houses conflicts.

Hutchinson et al (2006) study investigated the extent to which UK homes with low indoor-temperatures could be identified from dwelling and household characteristics. They concluded that property and household characteristics provide only limited potential for identifying dwellings where winter indoor temperatures are likely to be low, stating this was likely to be due to the multiple influences of home heating, including personal choice and behaviour. However it should be noted that the study only looked at data from households participating in the Warm Front evaluation, and hence all of them had already applied for (and/or had been awarded) a grant for energy-efficiency improvements. Thereby it is likely that houses included in the study were biased towards those having issues with providing cold environments and therefore the study results may not provide a true representation of building types.

In a study by Hong, Gilbertson, Oreszczyn, Green, & Ridley (2009) UK property characteristics such as building age and type were not significant and were found to be unrelated to thermal comfort.

8.2.3 Passivhaus

Mlecnik et al (2012) analysed German, Austrian and Swiss post-occupancy evaluation research results on nearly zero-energy dwellings and also undertook a survey of occupants of nearly zero-energy houses in the Netherlands. In the review of the literature, they report that comfort was an important parameter with regard to positive appreciation. They reviewed a number of studies which found that occupants perceive their living conditions to improve after moving into a passivhaus particularly with regard to winter thermal comfort and indoor air quality. They report that users of passivhaus often feel more comfortable during the winter than during the summer. Sometimes a less comfortable indoor climate in summer can be directly linked to design deficiency (for example, lack of shading or ventilation bypass) or technical deficiencies in the heating and ventilation systems.

8.3 Adaptive approach to building design and thermal comfort

Baker and Standeven (1997) and Nicol and Humphreys (2009) make the case that optimal indoor environments in a building are a function of its form, the services it provide and the climate in which it is placed. Nicol and Humphreys (2009) state that current international standards for indoor climate are based on the need for close definition of an 'optimum environment' for comfort, and compliance with them often contradicts the need for low-carbon buildings. Nicol & Humphreys (2009) propose that new standards are needed. Such a standard, they propose, would be building based, rather than environment based, giving greater freedom for the design of sustainable buildings. An added advantage outlined by them would be that no distinction would need to be made between buildings which are naturally ventilated and those which are air-conditioned (Nicol & Humphreys, 2009).

Baker and Standeven (1997) provide recommendations for architects in relation to building design and thermal comfort;

- Limit the extremes of thermal conditions and respond to seasonal variations by the inherent properties of the building
- Provide adaptive opportunity by environmental variety and user friendly building controls
- Allow visual access to outdoor climatic conditions and a simple "readable" architectural design.

Rijal and Stevenson (2010) conducted thermal comfort surveys and a window opening behaviour survey in the Sigma Home (on display at the Building Research Establishment, Innovation Park at Watford). Findings from the study support the comments of Baker and Standeven (1997) and Nicol and Humphreys (2009) in suggesting a need to design homes and build systems that meet the needs of a mid-range of temperatures, which have fast acting functionality when required, to suit temperature peaks and troughs.

8.4 Modifying their environment to get comfortable

Chappells and Shove (2005) argue that instead of providing specified comfort conditions, opportunities should be provided in which people make themselves comfortable. Several studies have been conducted looking at how people get themselves thermally comfortable in their own homes (Tweed et al. 2014, Vadodaria et al. 2010, Vadodaria, Loveday, & Haines, 2014, Gram-Hanssen 2010 and Kuijer and de Jong 2012). These studies used mixed approaches of surveys, in-depth interviews, audio tours and other probing methodologies. Findings of note from these studies are presented in the next sections.

8.4.1 Home improvements

Vadodaria et al (2010) conducted in-depth interviews with householders to describe how they maintain comfort in their everyday lives, with regards to home improvements it was found that householders were motivated to make home improvements by a range of factors, including discomfort –particularly in replacing windows or floors to minimise draughts.

Kuijer and de Jong (2012) conducted a workbook and interview study investigating current heating practices. They found that improved insulation of homes reduced heat loss and in parallel, draught. They note that there are limits to the levels of insulation that are considered acceptable. Commenting that draughts are unpleasant, but when it is called ventilation, it is good and necessary, they note that windows are left ajar even in winter and a warm body in combination with fresh surrounding air is a preferred condition of comfort.

8.4.2 Furniture

Humphreys et al (2011) discuss the design of furniture used in conjunction with open fires, pointing out that, in the past, upholstered chairs, in which the person sat near the fire, sometimes had a high back and ‘wings’, which reduced cooling by draughts. This chair would also become heated by the same radiated heat from the fire, and consequently the occupant would not lose excessive heat to the cooler room surfaces behind. They also comment on the use of tall screens behind chairs used to provide a further comfortable ‘micro-climate’. Humphreys et al (2011) cites Heschong (1979) stating that this increase in radiated heat from these additional surfaces provides a condition often considered desirable for comfort, and one often associated with cosiness and ‘thermal delight’.

Kuijer and de Jong (2012) comment on the use of the futon in Japan. The ‘futon’ is a foldable bed that can be spread out in the evening in a space used as living room during the day. These multipurpose rooms have also made it necessary for other furniture and appliances to be easily portable and moved out of the way, such as for example the hibachi and other portable heaters, already discussed.

8.5 Supplementary heating and localised heating

Studies by Vadodaria et al (2014), Kuijer and de Jong (2012) and Tweed et al (2012) use in depth interviews and observed behaviour to explore how people get comfortable in their homes. The results provide insights into the use of additional localised heating. Results of relevance are presented below.

Vadodaria et al (2014) conducted an analysis of measured temperatures in a sample of solid wall dwellings in the UK. In addition to the quantitative temperature data collected in the CALEBRE research project, qualitative data were also gathered on thermal comfort sensations. The qualitative data provides an insight into whether the temperatures measured in the homes were acceptable or not to their occupants and suggested reasons for the discomfort and the action taken to alleviate it were also recorded. Results from the study show that the main reason reported for a householder being too cold was that the heating was not turned on in their house or the room in which they were located. In some cases, this was because the heating was programmed to come on at a later time. In other cases, the householder did not use their central heating system and instead switched on a local heater once they entered a particular room or put on more clothes. This suggests the capacity to use heating systems, but other factors overriding and preventing its use through choice.

Kuijer and de Jong (2012**)** propose and illustrate a practice-oriented approach in which design opportunities offering people a wider variety of ways to achieve thermal comfort are identified and explored. In their study they provide a range of products which provide localised heat and assess their effectiveness from observations and interviews probing user's experiences. In their paper, they also comment on observed practices in Japanese homes where localised heating is more common practice. Noting that Japanese households generally and historically adopt more person-oriented heating practices and a great diversity of more local heating systems can be found, like the hibachi; a portable charcoal fuelled heater designed to sit close to for warmth. Another example of a localised heating product is a 'kotatsu'; a low table covered by a comforter that is wrapped around the waist area and captures the heat of the heating unit placed under the table. Other local heat sources are electric carpets – which are slowly replacing the kotatsu – and the 'yuutampo', a type of hot water bottle.

Tweed et al (2013) conducted five in-depth interviews with occupants of UK residential buildings, one interviewee reported using a portable halogen heater in the living room as supplementary to his storage heaters which they found to be inadequate by the evening.

Kelly et al (2013) found that homes that have secondary heating systems in the living room have lower internal temperatures when compared to homes that do not have secondary heating systems. This implies living room heaters give occupants the opportunity to limit heating to the main room in the house, therefore lowering the mean temperature in the rest of the house.

8.6 Ventilation

8.6.1 Opening/closing windows/doors

A study by Tweed et al (2014) used surveys and in-depth interviews in Wales to provide an insight into how people achieve thermal comfort and the driving mechanisms behind their actions. Results showed that the occupants' control of thermal conditions extended beyond the conventional adjustment of heating system controls to include operable elements of the building fabric. Tweed et al found that there was evidence of significant use of windows and internal doors to regulate air movement and temperatures. Reporting that the drivers behind occupant behaviours related to heating are inconsistent, "On some occasions, cost is seen to be a dominant factor in decisions about heating, while in others, comfort is the major driver, or, as noted in many cases, the perceived need to 'air' the property can override all other concerns such that nearly all of the occupants were prepared to sacrifice heat (and money) to ventilate their properties even during cold spells in the weather first thing in the morning". Tweed et al (2014) conclude that the opening of windows is influenced by non-thermal concerns, i.e. fresh air, removal of condensation and as a precaution to protect against mould. Banfill et al (2012) also report door and window opening behaviours as commonplace in older homes, for a wide variety of reasons including privacy, noise regulation and getting fresh air. Pink and Leder-Mackley (2012) identify that making a sensory connection with the outside is an important aspect of the home; to hear birdsong or feeling the breeze, emphasising the holistic importance of ventilation.

An extensive literature review by Fabi, Andersen, Corgnati, & Olesen (2012) was conducted to look into the drivers for the actions taken by the occupants (including window opening and closing) and to investigate the existing models in the literature of these actions for both residential and office buildings. Fabi et al (2012) concludes that the effectiveness of natural ventilation is strongly dependent on characteristics of ventilation openings and their controllability (aspects closely related to the type and size of the windows and its placements within facade). The window opening and closing behaviour is strictly connected to the building characteristics.

Gram-Hanssen (2010) used practice–theory and reports on five detailed descriptions of individual participants heating / cooling practices in the home. Gram-Hanssen (2010) found that all the interviewed households practice indoor climate regulation and that they employ different habits with regards to how they interact with doors, trickle vents and windows every day.

8.6.2 Mechanical ventilation heat recovery (MVHR)

Mechanical ventilation offers a way of providing heat in conjunction with air circulation and this in turn may affect the ‘need’ to open windows. Different research (cited in Mlecnik et al. 2012) based on indoor air quality measurements suggest that the air quality in passivhaus with mechanical ventilation was better than that of conventional buildings.

8.7 Psychological Variables

In a literature review of field experiments on thermal comfort by Heijs & Stringer (1988) it was shown that the temperature range of comfortable conditions was considerably greater than in the artificially created atmospheres of climate chambers. They suggest that individual differences are also more important and to a large extent these can be accounted for by psychological variables, such as knowledge and experience and also demographic variables such as gender, age, place of residence. Furthermore, Heijs & Stringer (1988) suggest that there are also probably influences from lighting and furnishing on the perception of thermal comfort.

In 1980, Rohles (cited in Heijs & Stringer, 1988) reports a number of experiments in which investigated the role of psychological variables. He found that interior design, temperature feedback (i.e. a presence of a visible room thermometer), knowledge/awareness of operating heating systems (informing occupants that a heating system was working or not) all affected perceived thermal comfort of occupants in climatic chambers.

Similar results regarding interior design were also reported by Oseland (1995), in which it was demonstrated experimentally that people feel warmer in their home than they do in their office at the same temperatures. Oseland mentions as a possible reason the presence of furnishings (i.e. carpet, wall paper and furniture), as people tend to judge rooms with such features as being warmer.

The 'hue-heat' hypothesis has also been investigated by a number of researchers (Fanger et al. 1977; Bennett and Rey, 1972 – cited in Heijs & Stringer, 1988). The hypothesis proposes a relation between the hue of lighting and the perceptions of thermal comfort: red tints should induce a warmer feeling. In the blue lighting condition a somewhat higher temperature will be preferred. Greene and Bell (1980) undertook an extensive experiment (n = 144) in which three factors were varied: gender, temperature and colour. Variation in colour was applied to the walls, while the furnishing stayed the same. No effects were found of gender or of colour on the subjective estimate of temperature, but the red environment was evaluated more positively in terms of personal comfort.

8.8 Clothing

Kuijer and de Jong (2012) used in-depth interviews to provide insights into the use of layers of clothing. They found that although the most common response to feeling cold was turning up the thermostat, there was wide acceptance by participants putting on extra sweaters, indoor slippers and blankets.

Rijal and Stevenson (2010) report changes in layers of clothing worn indoors correlated with the varying outdoor air temperature from season to season.

9 Delivery methods

9.1 Literature search results

Heating and cooling can be delivered in a variety of ways- through heat emitters such as radiators or convection heaters or hot /cold air systems. Reports on the preference for delivery mechanisms of heat in domestic sector in the context of thermal comfort are few. The majority of the literature focuses on the physical performances of the delivery system themselves rather than the subjective experience of comfort gained from these devices.

Literature regarding different delivery mechanisms and thermal comfort tends to be within commercial settings with large scale heating systems (such as alternative HVAC systems), where system components are designed based on the industry standards such as ASHRAE (where comfort criteria are represented through comfort induces, PMV and PPD). In residential buildings, conditions are not quite comparable to those during the experiments for calibration of the PMV and PPD equations (Lomas & Kane, 2013)(Peeters et al., 2009). Furthermore, the majority of research studies of delivery methods used in office buildings tend to investigate the delivery mechanisms and their associated thermal comfort criteria through experiments in climatic chambers or simulation evaluations rather than in situ using real human subjects.

Therefore, this section presents summaries of some studies based on subjective preference / perceptions of different delivery mechanisms in residential settings by human subjects (end users) and, where appropriate, draws on example cases from commercial setting/contexts. In some instances, where information and sources are sparse, reference is made to some non-academic sources.

9.2 Residential heating

Heschong (1979), Shove (2003) and Humphreys (2011) provide accounts of the evolution of indoor heating/cooling systems starting from the evolution of the open fire through to central heating. Over the decades there have been technological advancements in heating systems and heat emitters within the home, moving from radiant heat emitters (the open fire) to convective heat emitters (storage heater, radiators, underfloor heating, convective fans etc.), from decentralised/ local heating systems in which heat is generated and limited to a single room or small area to central heating whereby each room is heated from a central generating heat source. Each system has its own set of thermal characteristics and has an effect on perceived thermal comfort.

Thermal comfort is defined by four environmental factors and two personal factors (Fanger 1970). From a delivery mechanisms' perspective, the four environmental characteristics that are manipulated are:

1. Air Velocity - heating systems that have less air movement have a better quality of thermal comfort. Heating systems that depend on forced movement of air or promote convection will have a diminished quality of thermal comfort.

2. Humidity – heating systems that maintain a moderate relative humidity (around 50%) have a better quality of thermal comfort. Heating systems that focus on only raising air temperature usually cause the relative humidity to fall well below 50% with a corresponding negative impact on thermal comfort.

3 and 4. Air temperatures and radiant temperatures – heating systems which maintain relatively equal air temperatures and the mean radiant temperatures have a better quality of thermal comfort. Heating systems that produce high air temperatures with little impact on the mean radiant temperature will have a diminished quality of thermal comfort (Mid-Atlantic Masonry Heat, 2013).

9.3 Type of heat and heating systems

Heat emitters typically provide heat through convection or radiation. An overview of each of these types of heat is presented here. High and low temperature heating systems are also discussed.

9.3.1 Convection

The air is a fast and relatively easy way to add heat to the home. However, when only the air temperature is manipulated the following unintended consequences occur. First, the air in the home becomes stratified – hot at the ceiling cold at the floor. Second, heating the air does not increase the radiant temperature. Instead the disparity between air and surface temperatures in the home increases. This means a person's body continues to radiate heat to the cool surfaces in the home even though the air temperature is warmer. The result is a cold and clammy feeling. Third, the stratification of air and the cool surfaces result in convection and increased air velocity (draught). Fourth, heating the air causes the relative humidity to drop lowering the apparent air temperature. Lower humidity dries out occupants' throat and skin and gives rise to static electricity (Mid-Atlantic Masonry Heat, 2013).

9.3.2 Radiant heat

While radiantly heating surfaces in the home is slower, it does not cause the unintended consequences that come with convective heat transfer. Radiantly heating surfaces in the home stabilises the air temperature at a comfortable level, does not cause draught and does not dry out the air. Experimental studies conducted by Dongen (1985, cited in LowEx (2004)) show a high appreciation by building occupants for heating systems that work primarily on radiant heat.

9.3.3 High and low temperature heating systems

Technological innovations in efficient heating systems are changing the way in which homes are heated (C Tweed & Dixon, 2012). New technological developments in heat production in the domestic sector tend to deliver heat at low temperatures, rather than high temperatures which we are used to and typically are characterised by having slower warm / heat up times. Example delivery system includes; wall and floor heating systems, air heating, enlarged radiators, fan assisted radiators and enlarged convectors. These delivery methods substitute the familiar high temperature sources of warmth, such as open fires, wood burning stoves or radiators with unfamiliar low temperature background heating to create a uniform thermal environment.

The radiant heat transmission components of low temperature systems are much higher than in other systems. Due to large surfaces and low temperatures, the radiant component of floor and wall heating is about 50–70 %. For conventional HT radiators this is 20–40 %. Therefore, the heat transfer by air is reduced and the air temperatures can be 1–2 C lower at the same comfort level. As previously stated experimental studies conducted by Dongen (1985, cited in LowEx (2004)) show a high appreciation by building occupants for heating systems that work primarily on radiant heat.

A study Eijdems and Boerstra (1999, cited in (LowEx, 2004)) showed that lowering the temperatures for heat distribution systems, besides the possibilities of savings in energy supply, gives additional benefits in terms of thermal Comfort (greater share of radiant heat transfer, less temperature gradients, better floor contact temperature, less draught and air turbulence).

Quick temperature fluctuations around a constant mean value can cause discomfort however; low temperature heating systems have a greater inertia than high temperature radiators or air heating. Furthermore Olesen (1997) states that the driving forces are smaller in low temperature systems due to large surfaces and low temperature differences. For these reasons fewer fluctuations occur. The inertia is often considered to cause discomfort at incoming solar radiation or sudden changes in internal gains. In this aspect, low temperature heating systems benefit from their 'self-regulating' abilities. Due to the small temperature ranges at which they operate, the heat supply reacts instantly on indoor temperature changes (Olesen 1997, Cited in LowEx 2004).

Some of the negative aspects associated with low temperature heating systems are that to work effectively they require well insulated and air tight buildings. Heating systems which rely on airtight buildings may result in insufficient fresh air being supplied and may thus lead to poor indoor air quality and related health issues. To avoid this problem, a mechanical ventilation system, such as a mixing ventilation system or a displacement ventilation system, for fresh air supply must be integrated with the low-temperature heating systems (Wu et al 2014). Such systems can result in local and/or global discomfort (Schellen et al, 2010).

Low temperature delivery methods and their implication for thermal comfort and the thermal experience are also discussed further in Tweed and Dixon (2012), de Dear (2011), Devine-Wright et al., (2014), Mlecnik et al., (2012), LowEx Guide book (2004).

The LowEx 2004 Guide book, presents a review of low energy systems and uses the term Low Exergy. Exergy is energy, which is entirely convertible into other types of energy. High valued energy such as electricity and mechanical workload consists of pure exergy. Energy, which has a very limited convertibility potential, such as heat close to room air temperature, is low valued energy. Low exergy heating and cooling systems allow the use of low valued energy, which is delivered by sustainable energy sources (e.g. by using heat pumps, solar collectors, either separate or linked to waste heat, energy storage etc.). The guide book , freely available online, summarises the work of the LowEx cooperation and is meant to help engineering offices, consultants and architects in their search for energy efficient heating and cooling systems. In addition, some background information is offered for real estate builders, building maintenance managers, political decision makers and the public at large.

There are differing views on delivery methods used in energy efficient heating systems. Devine-Wright et al (Devine-Wright, Wrapson, Henshaw, & Guy, 2014) suggests that the widespread adoption of super-insulated houses not requiring heating systems is unlikely since they contravene expectations of cosiness and glow for homeliness, warmth and sociability. Whereas Tweed and Dixon (2012) summarise that “the lack of high temperature heat sources in low carbon dwellings is unlikely to become a major issue, since it implies a loss of aesthetics component of thermal experience”. However they also state that “perhaps we shouldn’t underestimate the importance of aesthetics as an influence on people’s behaviour.” Tweed and Dixon (2012) report that, at least anecdotally, there is evidence to suggest occupants will subvert the intended low carbon operating strategy by introducing auxiliary forms of heating, commenting that many passivhaus buildings in continental Europe come with wood burning stoves to provide a top-up of high heat in the cold winter months.

De Dear (2013) reports that trends in new technological advances continue setting the directions for contemporary thermal comfort research, and that more research is needed. This includes:

- Whether the installation of such devices leads to new practices or becomes accommodated within pre-existing routines; currently this is poorly understood (Devine-Wright et al., 2014b)
- Widening our understanding of what people want (rather than merely need) in the design of low energy buildings (Tweed and Dixon, 2012).
- How the environment is perceived rather than measured (Tweed and Dixon, 2012).

9.4 Heat emitters

Some of the different types of heat emitters used in heating domestic properties and their associated thermal comfort and thermal experiences are presented.

9.4.1 Heating profiles

Brown (2011) provides an ideal heating profiles and provides illustrative examples of heat profiles provided by radiators, convectors heating and underfloor heating. The occupied zone for a simple space is from the floor to two meters above the floor. The ideal case is where the temperature reduces as it rises through the occupied zone with the temperature level at its lowest at the ceiling. Brown 2001 states that this is when people feel at their most comfortable, when their feet are a little warmer (by one 1°C) than their head. Figure 1 below is taken from Brown (2011) and presents temperature profiles for the ideal, radiators, underfloor heating and a convector heater.

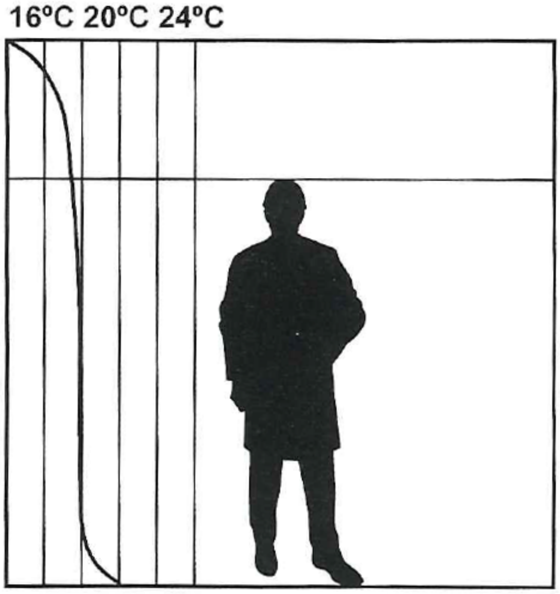
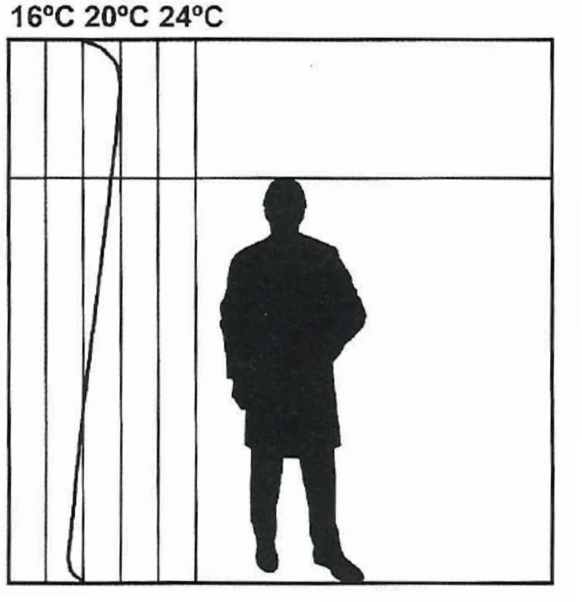
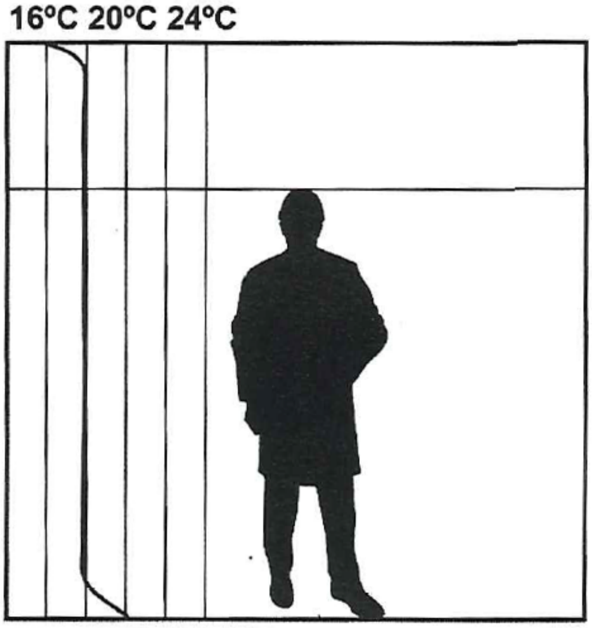
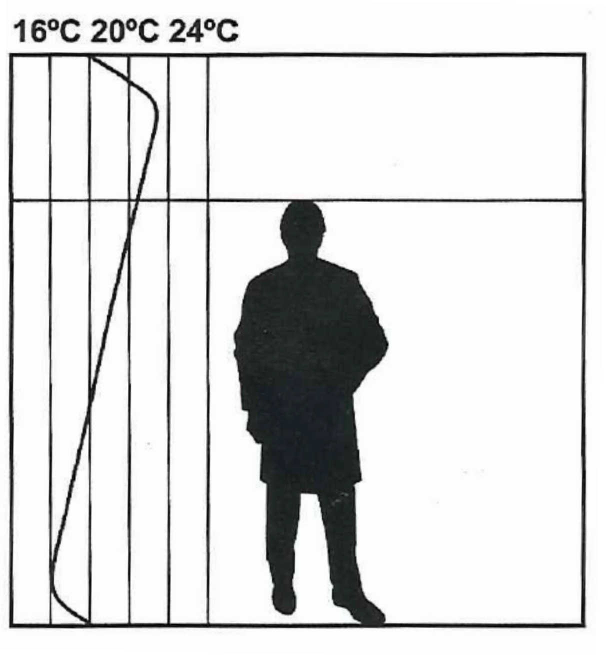
	
Ideal temperature profile	Profile for radiators
	
Profile for underfloor heating	Profile for Convector heating

Figure 1. Temperature profiles for the ideal, radiators, underfloor heating and a convector heater

9.4.2 Open fires

Rudge (2012) states that open fires provide radiant heat for those in direct line of the heat source but without heating the air, therefore comfort is possible despite low air temperatures. Humphreys, Nicol, & Roaf (2011) report that thermal radiation from open fires falls onto walls and other room surfaces and warms them; they in turn warm the room air in contact with them. In addition, fire places made of cast iron increase the convective heat either in front or behind the hearth. Humphreys, Nicol, & Roaf (2011) also comment on the use of additional furnishings historically used in conjunction with an open fire to maximise heat and comfort; for example the use of high back chairs and wings reduced cooling by draughts and the use of tall screens behind chairs were also commonly used to provide a further comfortable 'microclimate' quite different from the rest of the room. A negatives aspect of open fires on thermal comfort is that air goes up the chimney and this draws outdoor air into the rooms through cracks and openings and while this provides ventilation, it can also produce unpleasant draughts, especially across the floor (Humphreys et al., 2011, Rudge, 2012).

9.4.3 Stoves

In an survey and interview study by Petersen (2008) it concludes that the single most important motivation for having and using a stove is the sense of homeliness, cosiness and calm that the stove is felt to provide "A sense that is achieved from the sight of the flames and embers and the sound of the crackling fire as well as from the process of lighting the fire and just having the stove as a piece of furniture in the house". One participant commented that they used the lighting and enjoyment of the fire as a relaxation ritual. This conclusion is supported by findings from a study by Devine-Wright, Wrapson, Henshaw, & Guy, 2014 in which the importance of the visual appearance of the heat emitter is emphasised. Devine-Wright et al (2014) report that even when primary heating (including low carbon) heating systems provide sufficient heat to achieve thermal comfort; a visible glow is sought by occupants when external temperatures are sufficiently cold. Respondents valued visibility of a hearth for 'Cosiness and glow'. However the authors point out that their study looked at an older cohort and their findings may, therefore, be generation specific.

However, Humphreys (2011) reports on the negative effects of heat emitted by stoves reporting that although modern closed stove, fired by gas, wood or coal, burns fuel efficiently (perhaps up to 80%) this improved efficiency comes at a cost in terms of heating profile. Humphreys comments that stoves tend to produce a high temperature gradient between floor and ceiling, which can cause hot heads and cold feet. In addition, the reduced airflow up the chimney from stoves and/or in the case of modern stove, drawing air directly from the outside to avoid draughts, reduces the room ventilation. Humphrey also states that the output from the stove contains a smaller proportion of radiant heat, and its radiation is diffuse; so the benefit from the direct radiant beam can be much smaller than with a traditional open fire (Humphreys 2011).

9.4.4 Panel radiators

Conventional panel radiators do radiate heat, however typically 70% of the heat is emitted by convection and only 30% by radiation, depending on the operating temperature and type (Brown, 2011). Panel radiators produce a negligible difference between the air temperature and the globe temperature measurement that takes account of radiant temperature; therefore radiators (unlike their name suggests) primarily provide convective heating – heating the air (Rudge 2012). However in a study by Ali & Gaber Morsy (2010) results may suggest that different thermal experiences are perceived from panel radiators compared to convective heaters. In Ali's (2010) study they compared radiant panel heaters with conventional natural convective heating in terms of thermal comfort, it was found that a room heated by panel radiators although maintaining a lower ambient air temperature than the convective system, it provided equal levels of comfort perception on the test dummy head. At the same time Ali (2010) also found that two radiant panel heaters used in the study saved up to 39.1% of the energy consumption compared to the convection heater at almost same outdoor temperature.

9.4.5 Under floor heating

Conventional underfloor heating consists of a plastic heating pipe or heating cable laid beneath a floor surface. The floor surface temperature is deliberately kept below 29°C. spite the low surface temperature heat is typically emitted in proportions of 60% radiation and 40% convection, which are very similar proportions to high gas radiant tube heaters (Brown, 2011). Browns heating profiles for underfloor heating closely map the ideal profile. Brown states that underfloor heating provides minimal temperature rise between the floor and ceiling and in very high spaces the underfloor heating profile would move even closer to the ideal profile with the temperature reducing as height increased. Similar results are reported in computer simulations, laboratory and field experiments, where a clear difference of vertical temperature gradients was found between floor and ceiling for high temperature radiator heating conversely with underfloor heating, it was found that there was practically no temperature gradient in well-insulated buildings (Dijk et al. 1998, Olesen 1997, Cox et al. 1993 – all cited in LowEx 2004).

In a report by Low Ex 2004 it states that heated floors raise the comfort for all kinds of users and floor coverings, like carpets, are not needed for walking barefoot or sitting on the floor. Havenith (2001) reports that under floor heating systems may be preferable for older occupants. Peripheral vascular reactivity decreases with age, leading to more perfused extremities with high heat loss and Havenith suggests that this could be counteracted by such floor heating. Hashiguchi, Tochihara, Ohnaka, Tsuchida and Otsuki (2004, cited in Devine Wright et al (2014)) also report that underfloor heating could be considered to be a better heating method for older people to live comfortably and safely because, in contrast to other heating equipment such as an oil heater, air conditioning system etc. underfloor heating does not produce dirty air or emit a high velocity air flow.

9.4.6 Forced air or fan emitters

One of the concerns regarding forced air heaters in the movement of air that they create. Research indicates that, within comfortable range of temperatures defined in standards ISO 2005 airflow with velocity fluctuations between 0.5Hz and 0.7 is perceived as more uncomfortable than airflow with lower or higher frequency fluctuations (de Dear et al, 1993 and Ring et al, 1993 cited in de Dear 2014). However, de Dear et al (2013) discusses the 'Positive hedonic' aspects of air movement and these include; aerodynamic pleasure, breeze, aesthetics of air, thermal delight. De Dear also comments that the most recent revisions of thermal comfort standards include estimates of how much warmer the comfort zone can be stretched by increasing air speeds up to levels that in earlier versions would never be permitted without a requirement of individual occupant control of the air movement.

Humphreys et al (2011) and Humphreys (2011) recommend avoiding forced air emitters in bathrooms where the body might be wet, increasing thermal discomfort; radiant heat is best in this environment.

9.4.7 Cooling – air conditioning in residential homes.

Although the use of air-conditioning in the UK is uncommon at present, ownership could rise steeply if temperatures were a few degrees higher and if people were to be in a position to switch on air conditioning rather than using other methods to keep cool. Outdoor summer temperatures in the south of the UK are now occasionally close to the American threshold for air-conditioning (Institute, 2014).

9.5 Localised heating

Localised heating is where heat is generated and limited to a single room or small area.

The Japanese have generally and historically adopted more person-oriented heating practices and a great diversity of more local heating systems can be found in Japan, like the hibachi; a portable charcoal-fuelled heater designed to sit close to for warmth. Another example is the widespread habit of heating the toilet seat instead of the entire toilet space (Kuijer and de Jong, 2012). However changes in family lifestyle have led to more time being devoted to individual activities at the expense of joint activities and Japanese houses have changed towards heating more than one room in the house and heating entire rooms rather than individual bodies (Wilhite, 1996).

In the UK, houses were also historically heated using localised heating such as the open fire, and much of family life occurred round the hearth (Devine-Wright, 2012). However with the development of central heating, people now tend to heat all the rooms in their house and this is also reflected in changes in lifestyle.

In a report by Humphreys et al (2011) they challenge the perception that houses must be heated to modern standards and explore achieving comfort in an older house using background low temperature heating and reverting back to localised heating in which local supplementary heaters are used to create warmth as required. The authors comment that such a strategy does not attempt to provide a uniform indoor temperature but create thermal micro-climates when and where required, in a system in which occupants adapt both their building and themselves to stay comfortable. The report focuses on residential properties particularly those built before 1919. The report discusses the idea behind the proposed heating strategy, appliances that may be appropriate to provide warmth, associated comfort and health issues and the importance of adaptable clothing.

9.6 Office / commercial context

Heat / cooling delivery systems in office buildings have initially strived to attain a steady thermal environment for their occupants aimed at satisfying respondents in line with PPD and PMV (de Dear ,2011, Zhang et al., 2010). However, research has shown that in practice, most built environments present more complex thermal settings to the occupants. There is now an emergence of new technological evolutions in HVAC systems such as chilled beams, radiant ceiling panels, and displacement ventilation (DV). These systems have arisen, in part, in response to the energy efficiency imperative (De Dear, 2013). However these systems also result in producing more complex, non-uniform thermal exposures to occupants. There have also been developments towards providing Personalised Environmental Control (PEC) systems which, by their very nature, result in non-uniform thermal environments. An extensive review conducted by de Dear (2013) provides good overview of the aforementioned systems and only a short summary of some of the literature regarding DV and PEC systems is presented here.

9.6.1 Personalised environmental control (PEC)

Occupant interaction with the building and its systems is a significant determinant for occupant satisfaction and thermal responses (De Dear 2013). A number of systems have been developed and tested that provide an individual with the control of localised heating systems. The aim of these controls is to enable an individual to meet their own unique thermal comfort requirements. These personalised systems have had a variety of names: Task ambient conditioning (Zheng, Jing, Shi, & Zhang, 2009), local thermal distribution, PEC, personal ventilation (Kaczmarczyk, Melikov, & Sliva, 2010 and Melikov, 2004), Personal environmental module. The type of heating/cooling systems under the control of these systems may include fans or local duct outlets, heating panels, radiant or convective heaters, warm or cooled surfaces on chairs, desks and floor.

Whilst the research in the domestics sector is limited, further studies relating to localised heating / cooling can also be found in the context of vehicle interiors (Parson 1993, Holmer 2005, Parsons, 2002, Zhang, Wyon, Fang, & Melikov, 2007, Lustbader, 2005). A study by Oi, Yanagi, Tabata, & Tochihara (2011) conducted in climatic chamber but replicating a car interior, found that the room temperature at which occupants felt a 'neutral' overall thermal sensation was decreased by about 3°C by using the heated seat or foot heater and by about 6°C when both devices were used.

9.7 Body part effect

In complex thermal environments (with radiant floor and ceiling, stratified environments, solar radiation or warm/cold windows) localised sensation and discomfort determine whole body thermal sensation, acceptability and preference. De Dear (2013) provides an example – subjects whole body heat loss may not be far from zero but if their hand is cold, they will probably describe the overall environment as uncomfortably cold. The same degree of face cooling by convection may feel pleasant or unpleasant depending on whole body thermal state. This will feel pleasant when the whole body thermal state is warmer than neutral and unpleasant when the whole body state is cool.

Zhang et al (2010) collected subjective local comfort and sensation responses to steady state, non-uniform and transient thermal stimuli, but their approach consisted of a series of climate chamber experiments with human subjects.

Understanding how different groups of people respond to hot and cold stress can have a significant impact on their environment and comfort levels. This is a particularly important and evolving area of study to correspond to changes in society. Increasing single occupancy homes, an ageing population, and increasing obesity and other health conditions are all fairly recent demographic developments that affect the way we heat and cool our homes and therefore, our thermal comfort.

10 Implications for HEMS

The following implications for HEMS design are drawn from a reflection of the findings of the literature review.

1. Currently HEMS just measure air temperature, ignoring the five other parameters of Fanger's model and additional adaptive measures. Future HEMS should take account of more factors to provide a more satisfactory thermal environment. Some of these parameters will have more influence than others e.g. activity level.
2. HEMS could monitor physiological indicators such as vasodilation, vasoconstriction, piloerection, sweating and shivering but these are unreliable indicators of thermal comfort. HEMS do not need to monitor core temperature because these are relatively stable within the likely domestic environment and changes to core temperature are effectively controlled by the thermoregulatory system. Skin temperature is an unreliable indicator of thermal comfort and so there is little benefit in HEMS monitoring this as part of domestic heating control.
3. HEMS must be seen as an extension of people's adaptive opportunity to allow them to be able to use heating and cooling systems as part of maintaining their thermal comfort. HEMS must provide the perception of control and be easy to use by all householders. This will be particularly important for older people who may choose to use heating all year round, as the benefits of a well-designed system will be effective over a longer period.
4. HEMS should account for activity level and health, but not necessarily age, although older people are generally less active and have more health conditions – a bigger influence on thermal comfort than age alone.
5. HEMS could measure a multitude of demographic factors (ethnicity, weight, gender, etc) to make an accurate profile of individual occupants within a household, but this is likely to be beyond what most occupants are prepared to do and may still provide inaccurate assumptions of thermal requirements.
6. At neutral temperatures, HEMS do not need to take account of gender of occupants but at cooler temperatures (<18°C) females express more dissatisfaction than males. HEMS should therefore ensure temperatures do not drop below 18°C.
7. HEMS should ensure household temperature do not drop below 15°C for elderly occupants in particular, due to increased health risks as a result of circulatory disorders.
8. HEMS should control both heating and cooling to provide a thermally comfortable environment year round, including avoiding overheating in future summers.

9. HEMS should continue to take account of and control hot water use as well as heating.
10. HEMS should to ascertain when occupants want to be warm rather than when the heating should be on.
11. HEMS should detect occupancy patterns so that heating matches occupancy use of the dwelling.
12. HEMS could account for occupants' changing expectations of thermal comfort by adapting seasonally. This might mean a variable thermostat set point as the seasons change.
13. HEMS must be tolerant of the varied thermal environments in homes in order to maximise efficiency, as occupants are happy to take adaptive measures.
14. HEMS must be able to control the thermal environment in different zones of the house to meet the needs of occupants undertaking different activities in different rooms.
15. HEMS could utilise zonal control to provide cooler bedrooms to avoid heat stress at night; a cause of disturbed sleep. Cold stress at night is generally avoided in the UK due to behavioural adaptation of duvets and bed clothes. There is no physiological difference why room temperature should be different when people sleep; preference is as a result of behavioural adaptation.
16. Occupants like a visible heat source to provide a cosy atmosphere. HEMS should therefore not exclude this and could offer a 'cosy mode' – activating other thermal comfort stimuli.
17. HEMS could provide alternative strategies for achieving thermal comfort without using the heating system, e.g. opening doors, closing curtains, wearing more clothing, undertaking activity. As this might seem unacceptable to householders, this could be accompanied by feedback about potential benefits such as cost or carbon savings.
18. HEMS must work effectively with the range of heating systems including low temperature heating from renewables.
19. HEMS could monitor and maintain relative humidity below 60% to minimise presence and effect of allergens. Increasing air changes to 1.3 per hour will help reduce moisture and indoor air pollutants, but would need mechanical heat recovery to avoid heat losses.
20. HEMS should be able to detect and control ventilation within the home, requirements for which may vary throughout the year. At neutral temperatures, air movement of up to 0.4m/s is not a strong influence on thermal comfort, but at higher and lower temperatures HEMS may need to take into account air movement. This is, however, heavily influenced by personal preference, seasonal change, social and cultural norms and requires further investigation.

21. There is a relationship between obesity and the thermal environment, however it is unclear what the implications for HEMS would be; this is a growing issue with the increase in obesity in the UK population.
22. Improved HEMS might raise people's expectations of thermal comfort, as the perception of a more sophisticated system is a better service delivery.
23. HEMS should take account of, and work in conjunction with, secondary heating devices to provide a thermally comfortable environment as a system.

Currently work is focused predominantly on office buildings and more research into domestic thermal comfort is needed for accurate implications for HEMS. Many of the implications here are based on informed, but limited research. This is clearly an area where more understanding is needed to ensure HEMS and heating/cooling systems as a whole are able to meet user needs as well as work efficiently.

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