Proceedings of 9th Windsor Conference: ***Making Comfort Relevant***
Cumberland Lodge, Windsor, UK, 7-10 April 2016.
Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Diversity in Thermal Sensation: drivers of variance and methodological artefacts

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Abstract

In this paper we structure biological, psychological and background/experience drivers of thermal comfort variance and their relationships to develop a conceptual interaction model. The aim is to create a theoretical model containing a broad range of influencing factors that can be used for hypothesis generation. Furthermore, the paper provides a framework for assessing how much of the observed diversity in comfort votes may arise from imprecise instruments through the assessment of various forms of validity.

Current comfort models, both predictive and adaptive, focus on the prediction of conditions comfortable for an average person in order to derive comfort bands suitable for the majority of building occupants. Such models do not explain why we observe such a diversity of comfort votes from occupants of the same building. We argue that understanding diversity is important, both practically and scientifically, and that to do so we need to address the physiological, psychological, social, cultural and built-environmental conditions that give rise to observed diversity in comfort. It is expected that in doing so, the research community will both improve its scientific understanding of comfort, but also develop new ways of providing comfort that can create acceptable environments for more people using less energy.

Keywords: Thermal Comfort, Physiological factors**,** Psychological factors**,** Environmental factors**,** Diversity

1 Introduction

Over the past 30 years, both the nature, and the scale, of thermal comfort research have changed significantly. Fanger's PMV model (Fanger, 1970) has been complemented by the adaptive comfort model (Auliciems, 1981; de Dear et al, 2002; Nicol et al, 2010), with both embedded in standards and in wide use. Over this period, the technologies used to measure the environmental factors associated with thermal comfort have similarly evolved rapidly. Technologies for the measurement of ambient (and to a lesser extent radiant) temperature, relative humidity and air speed have become smaller and cheaper. This has enabled the scale of empirical thermal comfort data collection to increase substantially. This is illustrated in the ASHRAE RP 884 database (de Dear et al, 1998) that underpinned the development of the international standards for adaptive thermal comfort containing tens of thousands of data points across a wide range of countries.

There has, however, been less development in the area of identifying and measuring the personal factors that determine an individual's thermal comfort. Whilst metabolic rate and clothing level have long been understood to be important drivers of thermal comfort, our methods of measuring both these parameters have evolved little over the past 30 years - particularly in the context of field studies. Similarly, while there has been a proliferation of thermal comfort concepts - some well-established such as thermal sensation and thermal preference, and some more recently created/revived such as the importance of control, thermal acceptability and alliesthesia - there has been little emphasis on the development and testing of instruments to measure these comfort concepts.

There has similarly been comparatively little work on theorising thermal comfort post the development of the Adaptive Comfort Model. This is not to say that there haven't been signficant individual contributions (e.g. de Dear, 2011; Schweiker et al., 2012; Hellwig, 2015), more that there has neither been a consistent attempt to integrate new ideas emerging from the physiology and psychology communities into our understanding of comfort, nor to specify additional drivers related to behavioral, physiological, or psychological adaptive processes as suggested by Schweiker and Wagner (2015). Both the fields of physiology and psychology, have seen significant theoretical and methodological developments of direct relevance to comfort research in recent years, and we argue that the integration of best practice in these fields can only serve to improve our understanding of thermal comfort.

In this context, the aim of this paper is to simultaneously seek greater conceptual clarity on what thermal comfort concepts to measure, discuss mechanisms for the development of better instruments for measuring them, and suggest a conceptual model that can explain what factors drive diversity in comfort.

2 Why diversity matters

As Nicol et al (2012, Figure 10.6) note with respect to the plot of comfort votes vs. indoor operative temperature: "...One of the most instructive things about this for those who are unfamiliar with field survey data will be how scattered the data are.” An inspection of such a plot quickly reveals the diversity of temperatures at which people report feeling comfortable. For any given temperature between around 22°C and 28°C; there are simultaneously people who regard that temperature as 'much too warm' and others that regard the same temperature as 'much too cool'. The traditional response to such diversity has been to run linear regressions between comfort votes and environmental parameters (notably indoor operative temperature in the case of the adaptive thermal comfort model) to determine the correlation, then to model thermal comfort as a linear relationship with one or more independent variables. Statistically however, this discards a great deal of useful information, and such diversity of responses within the population naturally invites the development of more complex statistical models able to explain the observed variance. In Figure 1 below (reproduced Figure 10.10 from Nicol et al, 2012), the regression of comfort vote against operative temperature explains around 16% of the observed variance in the data. The 84% of residual diversity remains unexplained but is a valuable resource for future explanation of additional factors driving diversity in comfort perception. It is typical to extend such analyses through the introduction of additional variables using multiple linear regression methods, but to date such analyses seldom extend beyond correlation with running mean external temperature.

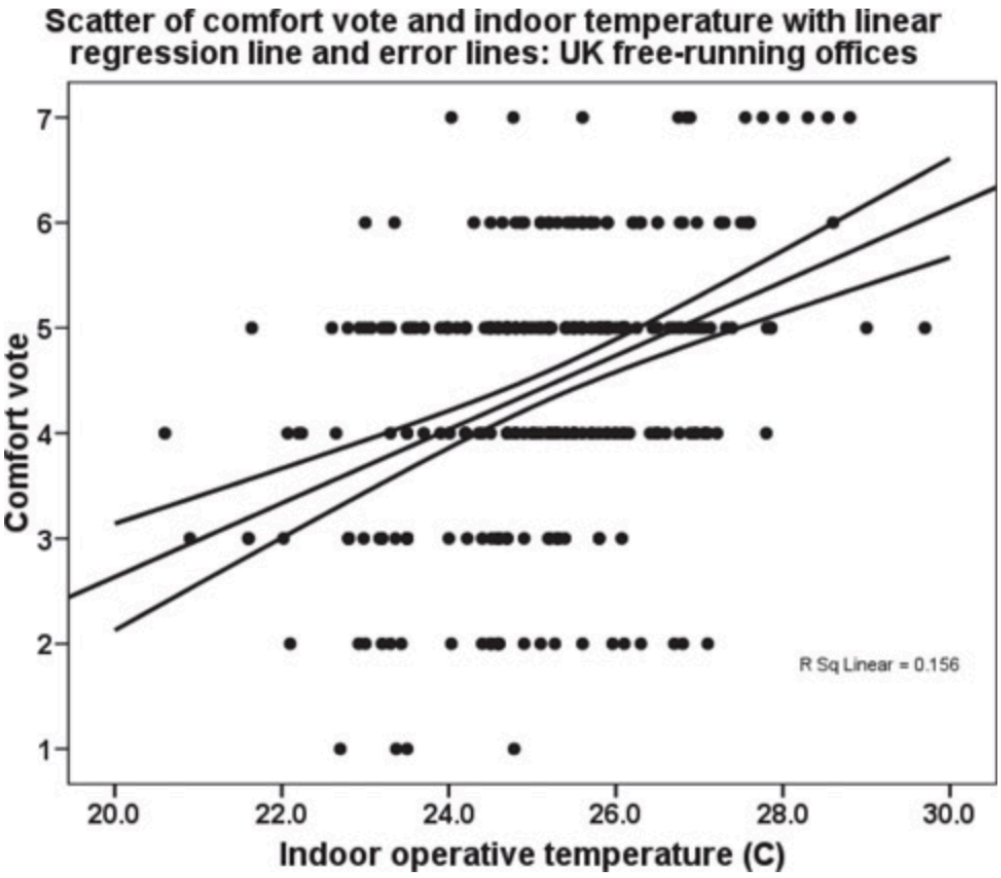

Figure 10.10 The comfort votes measured against temperature from Figure 10.6 with regression line for C on T_o added.

Figure 10.10 from Nicol et al (2012)

2.1 Practical reasons

Models that can better capture the diversity of thermal comfort requirements within the population are important for three reasons. Firstly, models that work on delivering neutral temperatures (the temperature corresponding to the centroid of the comfort votes against operative temperature plot) cannot deliver comfort to those participants that report finding such population-based neutral temperatures thermally uncomfortable. Studies have repeatedly found that the provision of neutral temperatures leaves between 10% and 20% of building occupants in thermally unsatisfactory conditions. Overcoming this requires provision of differentiated comfort conditions between individual offices, and within open plan offices. The design and provision of such systems however requires that we understand the drivers of diversity, and the likely diversity of comfort requirements needed to satisfy occupants in offices of different sizes and in different regions.

Secondly, understanding the diversity of comparable responses creates the opportunity to deliver comfort through different mechanisms than changing ambient temperature. There is considerable work addressing elements of this, for example provision of radiant heating and cooling, however the more we can understand the different mechanisms by which comfortable conditions can be created, the greater variety of ways we have at our disposal to deliver such conditions to occupants. Each mechanism through which we can deliver comfort will have different energy requirements, and will themselves vary in energy requirements depending on the spatial scale at which the technology is deployed. This leads to the requirement for models that can be applied to individuals, and to those parts of individuals more sensitive to heating and cooling.

Thirdly, the primary drivers of, and constraints on, thermal comfort provision are changing. Historically, the primary constraint has been energy demand in buildings, however this is increasingly being matched or surpassed by the requirements for the delivery power demand-side response energy services from buildings to support the deployment of smart grids. One of the primary distinctions between designing comfort systems under constraints on energy, and those under constraints of power, is that power constraints are far more temporally specific. Demand-side response (DSR) usually operates for the periods of hours requiring the capacity for buildings to drift in temperature over the short term. Dynamic thermal comfort models provide the information needed to maintain comfort by adjusting low energy intensity comfort vectors, whilst allowing high energy intensity vectors to drift during the DSR period.

2.2 Scientific reasons

In most scientific fields, model construction is an integral part of the process of knowledge construction. As outlined in Morgan and Morrison (1999), models form an essential element bridging theory and data. They act to support both the construction of new theories, and the testing of hypotheses based on existing theories. This process of theorising, model building, and measuring is at the core of the scientific method of progressively increasing understanding in a given field. The basis of scientific claims to knowledge, the ‘scientific epistemic warrant’, rests on the process of hypothesis construction and the testing of such hypotheses in unobserved cases. While there is some tradition of this in thermal comfort research, the bulk of the work to date has been descriptive, representing observed relationships in data in models (it is arguable that the adaptive relationship with external temperature is an example of this). Such models tend not to encode theoretically informed relationships expected to drive diversity in responses that can subsequently be evidenced through hypothesis testing.

In many areas, there is an increasing move towards the delivery of comfort through Personal Comfort Systems. This is evident both in the automotive and aviation sectors. Given the potentially considerable energy savings and improvements in occupant satisfaction that such systems can provide (Zhang 2015) it seems likely that such systems will increase within the built environment. As argued above, the design, commissioning, and maintenance of systems providing personal comfort will require models that are able to represent individual’s comfort requirements and help identify 'isocomfort'[1] lines and planes (areas of equal comfort) through the multidimensional space of variables that determine comfort for any one individual at any one point in time.

Developing such models will present fundamental challenges to our understanding of the interaction between human physiology and human psychology, and how both of these are

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[1] The term ‘isocomfort’ is a term used in ergonomics to represent positions of equal comfort in joint movement for people undertaking activities (e.g. Kee and Karwowski 2001). There is an analogous case where occupants report being equally comfortable under different combinations of environmental, physiological and psychological conditions in buildings.

impacted upon by the physical and social environments in which we live. Integrating the effect of such a diverse range of factors into models of thermal comfort is a fundamental scientific challenge that will require a new level of interdisciplinary collaboration across theory development, innovation in methods, and data collection in our field.

3 Conceptualising comfort

One of the most widely cited definitions of thermal comfort is from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE): 'That state of mind which expresses satisfaction with the thermal environment.' (ASHRAE 2013). The concept that is 'thermal comfort' is theorized as being determined by a range of physical, physiological, psychological and social variables in varying ways by the two primary competing theories in the field – Fanger's PMV model (ASHRAE 55; EN15251 (CEN 2007); ISO 7730) and Gagge's SET model (ASHRAE 55; EN15251 (CEN 2007)), as well as the broader academic literature. In both the standards and the literature this broad definition of thermal comfort is broken down into more specific constructs for the purposes of measurement.

A brief note on nomenclature is warranted here. We follow Markus (2008) and distinguish between *concepts*, i.e. the reification of all actual or potential instances of a set of experiences in the real world (in this case experiences relating to thermal comfort) – and *constructs*, which are the the instances of these in a specific population. Within a population, concepts and constructs are the same thing, however the distinction becomes particularly important in international comparative work where concepts transfer between populations and constructs may not. It is worth noting that the ASHRAE definition of comfort cited above neatly meets Mario Bunge's (1974) classical definition of a concept/construct, i.e. "…an ideal object, where the existence of the thing may be said to depend upon a subject's mind".

That said, it is also arguable that its theoretical foundations (Auliciems, 1981; Humphreys et al, 1998; de Dear et al., 1997) are not present in its current applied transformation into an equation with a single predictor (running mean external temperature). While a range of human (metabolic rate, clothing level) and environmental (ambient and radiant temperature, humidity and air speed) are integrated into our models of sensation of comfort, and are understood to be important, these factors remain less well integrated into our understanding of behavioural responses to thermal discomfort. In addition, psychological and broader conceptions of the social sciences are often completely omitted, such as the role of group interactions, social power and comfort practices. This conclusion was also reached by Rupp et al in their recent review article on thermal comfort research (2015 p.195)

> *Through this review of the literature it became evident that there is a gap in thermal comfort studies in relation to interdisciplinary research. The association with other professionals like psychologists, physiologists, sociologists, philosophers and even with other building related ones (architects and engineers that work with visual, aural and olfactory comfort) could be of great value for the development of an integral (systemic/holistic) research approach that may help to a better comprehension about sensation, perception and thermal comfort and its physiological and psychological dimensions.*

The PMV model identifies five concepts relating to thermal comfort that can be constructed and operationalized through scales when assessing the thermal environment. These are:

thermal perception; *thermal evaluation*; *thermal preference*; *personal acceptability* and; *personal tolerance*. (BS EN ISO 10551:2001) Each of these is a separate concept for which the standard provides a method of measurement (a single question with a scale of response choice options).

In addition to the above, there are a range of additional concepts widely discussed in the thermal comfort literature. These include perceived control (Hellwig, 2015); thermal alliesthesia (de Dear, 2011); adaptive opportunity and adaptive response (de Dear, et al 1998; Auliciems, 1981); thermal acceptability (Zhang et al, 2008); occupant satisficing (Leaman et al, 1999); and many others, the subjects of which inform the many review articles in this field.

4 Measuring comfort

Translating concepts and constructs into measurable quantities is an area that receives considerable attention across the social, psychological and physical sciences, but is one of the areas where we feel there has been a lack of methodological focus within the thermal comfort community. Each of the constructs identified in BS EN ISO 10551:2001 above is tested with a single question in which participants are asked to respond on an ordinal scale. It is important to stress in this context that the term 'scale' is used in two quite different ways in the thermal comfort and psychological literature. In thermal comfort literature, the term scale is used to refer to a series of thermal states or preferences (response choice options) offered to participants varying from two (e.g. "is the environment (local climate) acceptable rather than unacceptable"), through to bipolar scales with 11 or more thermal states. In both social and psychological research however, a scale refers to a series of questions each of which is trying to capture an aspect of an underlying construct that is not directly observable (a 'latent variable'). It is very rare for any such latent variables to be accurately measured by a single question scale. In psychology, there is a considerable methodological literature about how such scales (sets of questions) should be developed, and a considerable body of statistical science behind their evaluation. Each of these scales measuring a particular concept will be taken through a great deal of preliminary statistical testing using methods like Confirmatory Factor Analysis to determine which factors (individual questions within the scale) load onto the construct and provide sufficient convergent and discriminant validity to make the measure a good one of the concept (e.g. thermal preference). From the methodological perspective, it is therefore concerning that the five concepts in BS EN ISO 10551:2001 are each measured using a single questions scale. Indeed, the authors have had papers rejected from psychology journals on the basis of the concepts were not operationalised through a scale containing multiple questions per concept.

The lack of robust development and testing of scales (in psychology sense of that term) is a key area in which we feel further research is needed in this area. We feel that methodologically, concepts, constructs, the operationalisation of constructs through instruments, as well as testing aspects of measures' validity, are key to progress in thermal comfort research. This is particularly the case when integrating variables across disciplinary domains of building physics, human physiology and psychology. To do this, a sound intellectual framework for assessing construct validity is needed. One of the most widely used in the social and psychological sciences is the multitrait-multimethod (MTMM) matrix method (Campbell and Fiske 1959, cited and further developed by Brewer and Hunter, 2006). The MTMM method is widely used to test for convergent and discriminant validity of constructs. It also employs multiple methods per construct to distinguish between construct and method-specific variance. In addition, the emphasis within MTMM of applying ‘truly different methodologies’, is a natural fit to the testing of operationalisation of constructs using variables spanning different disciplines. To our knowledge, this method has yet to be applied to methods development in thermal comfort research.

The issue of quantifying variance arising from methods of measurement is central characterizing diversity in thermal comfort scores. True score theory states that ‘X’ (the observed score) equals ‘T’ (the true score) plus ‘e’ (random error) - i.e. X = T + e. The error term in this equation then being decomposed into two elements, random error ‘e_r’, and systematic error or bias ‘e_s’ giving: $X = T + e_r + e_s$. This extends in the case of studying variance to: $var(X) = var(T) + var(e_r) + e_s$ (noting that any addition to the variance term is captured in the ‘$var(e_r)$’ and the ‘e_s’ term simply shifts the mean of the observed values away from the true value of their mean). Any explanatory framework of variance of a concept in a population ‘var(T)’ (e.g. variance in thermal sensation) that is assessed through measurement ‘var(X)’ must distinguish between the true variance ‘var(T)’ and variance related artifacts of the measurement process ‘$var(e_r)$’. When we consider Figure 10.10 from Nicol et al (2012) reproduced above, measurement theory tells us that some component of the observed scatter will arise from measurement error ‘$var(e_r)$’ however to our knowledge to date there has been no complete systematic evaluation of this component of the variance in thermal comfort studies.

As Trochim (2006) notes: “True score theory is the foundation of reliability theory. A measure that has no random error (i.e., is all true score) is perfectly reliable; a measure that has no true score (i.e., is all random error) has zero reliability.” A variety of ways have been developed for the quantitative evaluation of survey instrument reliability. These include test-retest methods; parallel-forms reliability and internal consistency reliability (Trochim 2006). We are only able to find three instances of the quantification of reliability in thermal comfort scales in the literature. Lundgren et al (2014) assessed reliability of their Cold Discomfort Scale (CDS) using test-retest reliability methods. The CDS asks a single question “On a scale from 0 to 10, where 0 means not feeling cold in any way and 10 means feeling unbearably cold: How cold do you feel right now?” The test-retest protocol involved subjecting 13 male and nine female volunteers to -20˚C for one hour with testing every five minutes. The retest was done one week later (for experimental protocol see Lundgren et al 2014). Instrument reliability was assessed using a weighted kappa coefficient (effectively a within-subjects measure of correlation between the test and retest scores) comparing median values for the CDS as well as each five-minute score. The mean weighted kappa coefficient was 0.84 across all tests, with individual (five-minute) test result pairs having kappa’s varying between 0.48 and 0.86. This represents is a good degree of instrument reliability, but does still leaves a substantial (~15%) level of unexplained within-subject variation. While this can be represented through a variance error term ‘$var(e_r)$’, it may also be the case that the test subjects’ physiological and psychological states varied between the test and the retest. This opportunity for within-subject variance between tests is one of the predominant critiques of the test-retest approach.

Khogare et al (2011) developed a satisfaction scale for measuring thermal comfort in offices in India. They assessed scale reliability using the split-half method. This is a test for internal consistency and is conducted by devising a scale (in the psychological sense of a series of questions), randomly dividing the questions into two halves, applying the whole instrument to a sample, then calculating the correlation between the answers provided by the questions in the two halves. The correlation between the halves was 0.8. They then applied the Spearman-Brown prophecy formula to derive an estimate of the full test reliability of 0.88. This creates an implicit error variance term of 0.23 on the internal consistency measure ($1-0.88^2$).

The most extensive methodological evaluation of a thermal comfort scale found was that by Dehghan et al (2015) of their 'Heat Strain Score Index' (HSSI) - a measure of heat strain in the workplace. In addition to assessing scale reliability, they evaluated content validity, structure validity, concurrent validity and construct validity. They assessed scale reliability through a generalized version of the split-half method called Cronbach's alpha. This was applied as a measure of the reliability of each item (each question) relative to all the others and was used to determine which questions were to be included in final index. They developed a 40 item scale that was reduced to 21 items through reliability analysis. Overall the final 21-item scale had a reliability of 0.91. The index performed well against a range of physiological heat strain parameters such as aural temperature, heart rate and the physiological strain index with Pearson correlations ranging between 0.56 and 0.76. Whilst not directly comparable to established thermal comfort models in the buildings field, this suggests that exhaustive development and testing of thermal comfort indices can construct scales capable of explaining substantially more of the observed variance than is accounted for in existing models in our field.

5 Explaining diversity

5.1 Biological drivers

Biological drivers for thermal comfort relate to how individual biological characteristics such as body composition and age influence individual thermal requirements. In principle, these include both healthy and pathologic states. It is important to consider that the body is an adapting system, which adjusts its regulatory and controlling mechanisms for optimal homeostasis according to the environmental conditions. It has been hypothesized that thermal comfort, or thermal pleasure, serves homeostasis (Cabanac, 1971). This implies that conditions that cause the body to actively engage homeostatic regulatory mechanisms (e.g. shivering) may be perceived as uncomfortable, but because the body adapts, these conditions may become less uncomfortable over time (for acclimatization examples, see also van Marken Lichtenbelt et al. in these proceedings).

Body composition directly affects body tissue insulation and metabolic rate (Rennie, 1988; Cunningham et al., 1978). Both are major components that determine body heat distribution. For instance, matched for metabolic rate/surface area, the obese are likely to have warmer hands and colder abdomen skin than their leaner counterparts (Claessens-van Ooijen et al., 2006; Savastano et al., 2009). This spatial temperature difference is explained by the abdominal body fat, which acts as a thermal insulator for heat conducted from body organs to the skin. In the obese, this abdominal heat is instead dispersed to the hands (hence the warmer hands). In combination with clothing, the spatial distribution of skin temperature greatly influences the efficiency of heat lost to the environment, and also how the body perceives its own thermal state (Romanovsky, 2014).

In tandem with tissue insulation, resting metabolic rate (RMR) is largely determined by lean body mass, and body composition explains, for the major part, the RMR difference observed in subpopulations (e.g. males vs. females; or young adults vs. seniors) (Cunningham, 1980).

That is, with increasing age RMR decreases because of decreasing lean mass (e.g. skeletal muscle) and increasing fat mass. Other predictive models for metabolic rate, that do not use body composition directly, explicitly include those parameters that are influenced by body composition (i.e. body size, age and gender) (Harris et al, 1918; Roza et al, 1984). For thermal balance, these individual differences in metabolic heat production should be balanced by equal differences in heat loss, and therefore may contribute to variance in inter-individual thermal comfort.

5.2 Experiences or background

Our (thermal) experiences and variations in our background are additional drivers of variance. Just as we have varying physiological characteristics, we all have different experiences and backgrounds. Potential aspects leading to inter-individual differences include our climatic and cultural background. At the same time, and again in a similar way as our body is an adapting system, our experiences are constantly modifying our personal background.

5.2.1 Climatic

There is strong evidence that our evaluation of thermal conditions depends on our climatic background – both short term and long term (de Dear et al., 1997; Schweiker et al, 2009; Luo et al, 2016). However, the challenge remains to distinguish between physiological adaptation and acclimatization processes (see above) and non-physiological ones. Examples for the latter might be interlinked with psychological drivers such as emotions. A sunny day in a climatic context with a majority of days being rainy might lead to different emotions of happiness or joy and a distinctive acceptance of an overheated room, compared to a sunny day in a hot and dry climate.

5.2.2 Cultural

Our cultural background affects among others our perception of pain (Callister, 2003) and visual experiences (Segall et al., 1966). With respect to thermal sensation, as early as the 1980s, Auliciems (1981) had assigned differences in thermal sensation of people from England and North America to cultural differences. Auliciems postulated that these differences can be assigned to cultural differences in the way warmth or coolness is supplied to a given space.

5.2.3 Personal

On an individual level, our climatic, cultural, and personal experiences are part of our personality and our preferences. Beyond the field of thermal comfort, studies have shown a relationship between personality traits and well-being (Costa et al, 1980). Therefore, these factors might impact on thermal comfort as well. In the first study to relate personality traits to thermal sensation, Hawighorst et al. (2015) presented results from a field study showing a difference in thermal perception due to differences in the thermo-specific self-efficacy and climate sensitiveness. Schweiker et al (2012) found differences in the interaction with the thermal indoor environment based in thermal preferences. Nevertheless, these drivers are amongst the least investigated ones in relation to thermal comfort.

5.3 Psychological drivers

Psychological drivers might help explain inter-individual differences where different individuals experience the same thermal environment differently according to their specific cognitive or emotional state. They might also foster our general understanding of thermal comfort, such as that in certain settings comfort might be experienced differently by the majority of people because of a certain psychological state they are in (e.g. being very focused on a task as opposed to being at leisure).

Very few potential psychological impact factors on thermal comfort have been tested. However, based on findings in other fields, one can speculate that the followings concepts play a role. Note that the distinction between cognitive and emotional drivers is a loose one; it would need thorough testing to see whether an impact factor is mediated via a cognitive or emotional process. Historically, in psychology, these factors have been treated as largely separate entities, however, in recent years their interdependence has been recognized more. In general, cognitive processes encompass attention, memory, planning, language and problem solving. Emotional processes are harder to define and there is no consensus on a definition. The distinction is not crucial for this paper; and indeed, for the factors listed below, some could either operate via a cognitive or emotional process.

Pain research is in generally a field from which many important insights can be gained, due to the abundance of research, and also because one can argue that thermal stimuli and pain stimuli are to some extent related, or rather a thermal stimulus can turn into a pain stimulus when conditions are too hot / too cold.

5.3.1 Cognitive

Attention is loosely defined as ‘the behavioral and cognitive process of selectively concentrating on a discrete aspect of information’ (Anderson 2004), and has been extensively studied in psychology. The perceptual load theory as developed by Nilli Lavie (1995) postulates that in tasks involving a large amount of information (= high perceptual load), brain capacity is fully exhausted by the processing of the attended information, resulting in no perception of unattended information. On the other hand, in tasks of low perceptual load, spare capacity from processing the information in the attended task will inevitably spill over, resulting in the perception of task-irrelevant information. For thermal comfort that could mean that if individuals are highly concentrated on a demanding task, they will be less aware of the environmental conditions and would hence judge their thermal comfort differently than when experiencing the same environmental conditions when engaged in an undemanding task. The authors are currently testing this hypothesis, and are not aware of studies having tested it. However, some evidence that attention might play a role can be derived from an early study by Berry (1961). Whereas many other studies found that illumination impacts on thermal comfort (Candas et al, 2005; Huebner et al, 2014; Winzen et al, 2014; Fanger et al, 1977), he did not find such an effect. One reason might be that in his study participants were engaged in a highly demanding, unrelated task which might mean that they were less aware of their (thermal) environment. This speculation is corroborated by the fact that temperature conditions at point of expressed discomfort were of such values that virtually every person would be expected to feel uncomfortable, i.e. a very high value, whereas one would expect half the people to feel uncomfortable already at a much lower level.[2] Hence, different levels of being focused on a task might explain why people exposed to the same environmental conditions judge them rather differently.

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[2] For details on the Temperature Humidity Indicator that was used in this study, refer to https://www.google.com/patents/US3124002. Accessed 17.06.2015

Control has been identified as a concept of interest. It has been shown previously that having control over aspects of the local thermal environment can increase satisfaction with a wider range of temperatures (Paciuk, 1990; Brager et al., 2004; Schweiker et al., 2013; Schweiker et al, 2015) and allowing occupants to create a micro-climate is associated with greater worker productivity and significant energy savings (Zhang et al., 2010). Whilst one might argue that having control is inherently a physical property of the environment, it is likely to exert its influence via a psychological process such as increased self-efficacy. Even though there is initial evidence showing an influence of self-efficacy on thermal comfort (Hawighorst et al., 2015), its role is not yet fully understood.

5.3.2 Emotional

A recent study (Taufik et al, 2015) found that participants who were feeling positive about themselves after having received (manipulated) feedback about their environmental footprint judged the temperature in a temperature-controlled room to be higher than those who did not have a positive feeling induced. Hence, depending on how we feel, we might judge the same thermal conditions rather differently. Given that this study employed temperature estimates as opposed to comfort reports, it remains to be tested if participants also actually felt warmer, but it opens up an important avenue for further research.

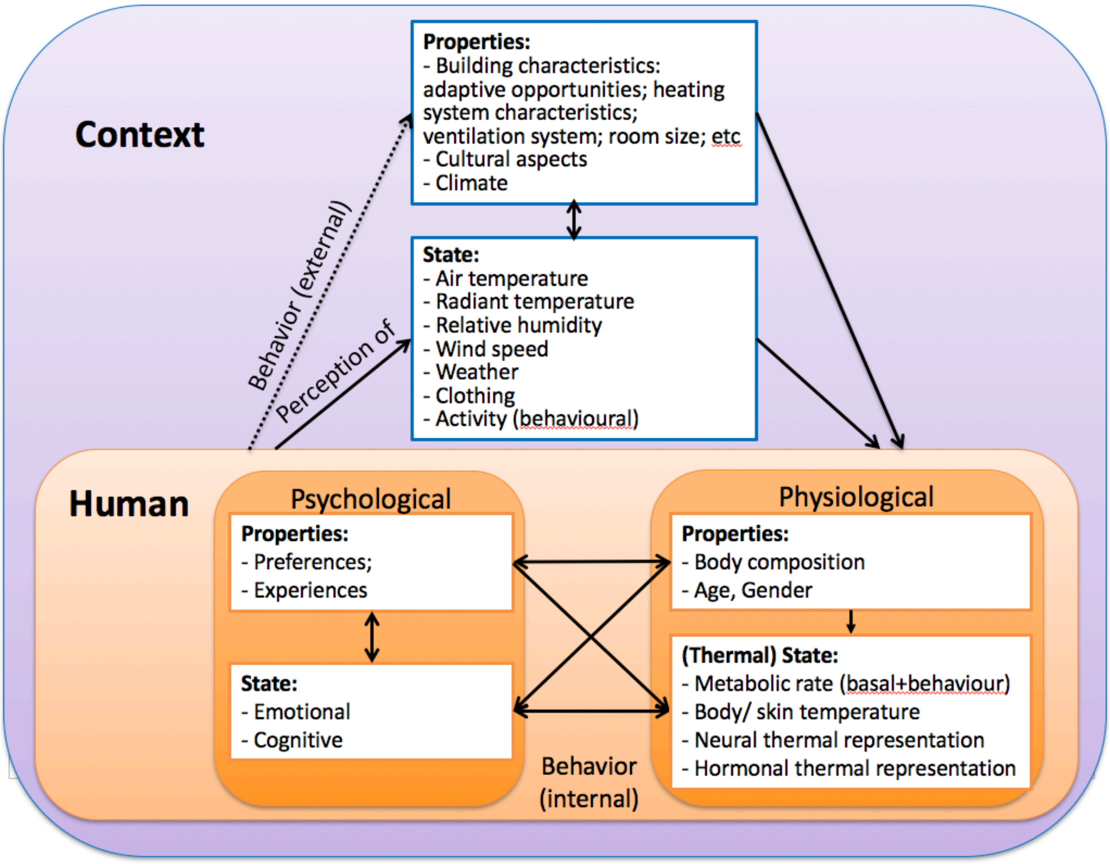
Research mainly from the area of social psychology has shown that being in a group alters behavior. One of the oldest and most striking examples is the conformity experiment from Solomon Ash (1951) which showed that social pressure from a majority group could affect a person to conform to what the majority said - even if the correct answer was clearly a different one. How exactly a social norm effect could play-out in thermal comfort perception remains to be tested – it could be that an individual picks up cues about the thermal environment from others to guide his or her behaviour. It is still debated whether the social norms effect acts through a cognitive or emotional process, with one opinion being that it has both components (eg Heywood, 2002) – a cognitive one, i.e. the memory of that is ‘right’, and an emotional one.

A recent study showed that tolerance of pain increases when engaging in a group activity, in this case singing (Cox, 2015). In a thermal context, obviously being in a group changes the physical thermal characteristics of the environment; however, it might be that there is an additional effect such as tolerance of a wider range of conditions when in a group. On the other hand, feeling socially excluded can also increase tolerance of both physical and emotional pain (DeWall et al, 2006).

This discussion of possible impact factors is far from exhaustive and it remains to be seen which factors do impact on thermal comfort, and if they do, whether they have a similar effect for all people or if not, what in turn determines inter-individual differences.

6 A conceptual model

The conceptual model is based on the description of drivers of variance above. A main distinction is made between the context and the human. Within the human, a further distinction is made between psychological and physiological aspects. Each of the three main elements is divided into *properties* and *states*. Here we define *properties* as those characteristics being (comparatively) stable over a certain period of time, and *states* as more transitory. This period might vary (e.g. building properties vs. body composition), but is significantly longer (months or years) than the time frame for changes in the state (seconds, minutes or hours).



The arrows denote hypothesized pathways and interdependencies. E.g. the human's state of skin temperature is influenced by the physical states and properties of the context. At the same time, the human can change the corresponding states and properties through adjustments to the built environment states (e.g. by opening a window), and properties (e.g. by replacing a single glazing window with a triple glazing one or a fixed window with an operable one).

6.1 Contextual factors

The influence of contextual factors on human thermal comfort are widely studied and will only be touched upon here. Properties of buildings, from the adaptive opportunities provided to occupants, through control of mechanical and natural ventilation, to the properties of heating systems ranging from ambient and task heating and cooling to system responsiveness, all impact both physiologically and psychologically on building occupants. Design decisions relating to spatial configuration, occupant density and emissivity of surfaces are likewise known or postulated to impact on comfort. States of buildings' thermal environments lie at the core of Fanger's PMV model and are the most studied class of comfort variables. While much is known with respect to these, there remain substantial areas in which our understanding of the drivers of individual occupant's different responses to these requires further work. There are clearly substantial interactions between states such as ambient and radiant temperature that underlie the psychological response to alliesthesia that require further research.

6.2 Human factors

Psychological states are temporary behaviors or feelings that depend on a person's situation and motives at a particular time – hence, they can vary across situations. Psychological traits are characteristic behaviours and feelings that persist across situations and time. Whilst both might impact on thermal comfort, the focus here is on the prior, i.e. states.

As discussed above, certain **emotions** might impact on our thermal perception, such as feeling positive about oneself, feeling socially excluded, and being part of a group. Similarly, **cognitive functions** might impact on our thermal comfort, such as attention.

These specific psychological factors might exert their influence on thermal comfort via our **perception of the environment**, such as that we might play less attention to the thermal characteristics of the environment when being in a certain psychological state. They in turn interact with our **preferences and experiences**. They also influence and are influenced by our **bodily state**. Emotions impact on physiological parameters such as heart rate and blood flow. On the other hand, physiological parameters and behaviours can impact on psychological states as well. For example, when the face is being forced into a smile by holding a pen between the teeth, people report a better mood than when maintaining a neutral facial expression (Strack et al, 1988).

Our physiological and psychological states and properties will impact on our judged thermal comfort and potentially on our **comfort related behaviour**.

6.2.1 Physiological factors

As described above, **body composition** (varying with **age** and **gender**) plays a major role in thermal state and temperature distribution over core and skin tissues. The body assesses its own **thermal state** from these tissue temperatures. With respect to appreciation of that thermal state, the dominant view is that the body compares its assessed thermal state relative to a set of fixed set-points to calculate a load-error (for a detailed overview see (Parkinson et al, 2015)). The underlying neurophysiology includes temperature sensitive neurons with distinct nerve types for warm and cold sensing (Benzinger, 1969; Hensel, 1981). These neurons have a non-linear activation pattern over tissue temperature, and transmit their information via distinct neural pathways to the insular cortex for perception and localization of thermal stimuli (Kingma et al., 2012). Note that this is a different brain area than the hypothalamus, which controls autonomous thermoregulation (e.g. shivering, sweating and skin blood flow). The thermo-sensory information is integrated through the neural pathway, and this is often described as being analogous to a set-point controller (Hammel et al., 1963, Cabanac, 2006). The neurophysiological basis for the reference signal (i.e. setpoint itself) is assumed to be non-dependent on temperature, but may scale with other factors (e.g. blood pressure, pathogens, melatonine, etc.), and therefore explain an adjustable set-point (e.g. higher core body temperature in fever, shifted set-point after acclimatization, no circadian effect in thermal sensation despite changes in temperature distribution) (Cabanac, 2006, Krauchi 2007). Therefore, the variation in internal mapping of the thermal state, due is likely to induce noise in observed in thermal comfort on individual basis, and between individuals.

7 Conclusion

Moving from a focus on mean responses to centrally managed environments, to understanding individuated drives of thermal comfort in increasingly comfort-differentiated environments, represents a considerable scientific challenge. We have sought to explore explanatory factors of observed diversity in thermal comfort data from field studies as a first step in elucidating the range of factors worthy of further exploration. The distinction was drawn between artefactual variance arising from poor instrument design and development, and the real (sometimes called 'aleatory') variability that can arise from environmental contextual drives, and drivers of individuation both physiologically and psychologically. This has led to development of a theoretical model that distinguishes between these realms and seeks to represent their interdependencies. The model further distinguishes between short-term 'states', and longer term 'properties' of the environment, mind and body that shape individual's perception of thermal comfort. It is hoped that the model proves useful in expanding the range of hypotheses that can be tested, and that such tests can help add evidential weight to, or call into doubt, relationships in the model.

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