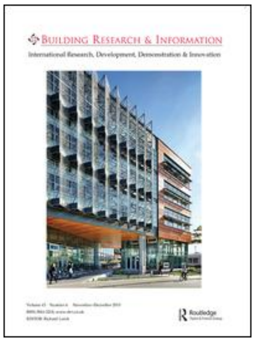

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INFORMATION PAPER

Thermal pleasure in built environments: physiology of alliesthesia

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International standards that define thermal comfort in uniform environments are based on the steady-state heat balance equation that posits 'neutrality' as the optimal occupant comfort state for which environments are designed. But thermal perception is more than an outcome of a deterministic, steady-state heat balance. Thermal alliesthesia is a conceptual framework to understand the hedonics of a much larger spectrum of thermal environments than the more thoroughly researched concept of thermal neutrality. At its simplest, thermal alliesthesia states that the hedonic qualities of the thermal environment are determined as much by the general thermal state of the subject as by the environment itself. A peripheral thermal stimulus that offsets or counters a thermoregulatory load-error will be pleasantly perceived and vice versa, a stimulus that exacerbates thermoregulatory load-error will feel unpleasant. The present paper elaborates the thermophysiological hypothesis of alliesthesia with a particular focus on set-point control and the origins of thermoregulatory load-error signals, and then discusses them within the broader context of thermal pleasure. Alliesthesia provides an overarching framework within which diverse and previously disconnected findings of laboratory experiments, field studies and even comfort standards spanning the last 40 years of thermal comfort research can be more coherently understood.

Keywords: adaptation, air-conditioning, alliesthesia, non-steady-state environments, physiology, thermal comfort, thermal pleasure, thermoreceptors

Introduction

The mainstreaming of adaptive comfort principles into the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) thermal comfort Standard 55 (ASHRAE, 2013) and EN15251 (2007) reflects a widespread awareness that thermal perception is more than an outcome of a deterministic, steady-state heat balance that has traditionally been used to define optimum indoor temperatures. Thermal alliesthesia has been proposed as a conceptual framework that differentiates the thermal pleasure in non-steady-state environments (de Dear, 2010) from the more thoroughly researched concept of thermal neutrality associated with steady-state environmental exposures (such as PMV/PPD). It may also offer a conceptual model of perceptual processes that determine why particular environmental configurations are unpleasant for some and pleasant for others.

This paper is the second in a series exploring alliesthesia in the context of indoor thermal comfort (de Dear, 2011). It begins with a brief summary of the hypothesis of alliesthesia and its potential to explain psychological states of thermal pleasure within the built environment. This introduction is based on a review of literature straddling the domains of thermal comfort, physiology and psychology. Subsequent papers in this series (1) will contribute empirical evidence from human subject laboratory experiments to support the hypothesis elaborated in this paper, and (2) translate this paper's hypothesis into a numerical model of thermal alliesthesia. The ultimate aim of the series of papers is to present alliesthesia as an overarching theoretical framework that reconciles previously contradictory strands of thermal comfort research and provides a more unified understanding of the many facets of thermal perception in the built environment.

Thermal alliesthesia

The psychophysiological term 'alliesthesia' was coined by Cabanac (1971) and subsequently elaborated and refined through a series of written works that spanned most of his career (Cabanac, 1979, 1992). The fundamental principle of thermal alliesthesia is simple: any peripheral (skin) thermal stimulus that offsets or counters a thermoregulatory load-error will be pleasantly perceived. For example, elevated air movement with the prospect of increasing net heat loss from skin tissue during exercise is likely to be pleasant. This is referred to as positive alliesthesia because the stimulus has the effect of removing excess body heat accumulated from physical activity. Whether a stimulus is deemed positive (pleasant) or negative (unpleasant) is known as hedonic valence, and is determined by the effect of peripheral (environmental) stimuli on thermoregulation in relation to the current thermophysiological state. Cold stimuli will be perceived as pleasant if the core temperature is elevated above normal temperatures, and warm stimuli will be experienced as pleasant if core temperature is below normal settings. Conversely, warm peripheral stimulation when the subject's whole body thermal state is warmer-than-neutral or cool peripheral stimulation when cooler-than-neutral will lead to negative alliesthesia – which is unpleasant.

A clear example of thermal alliesthesia was reported by Mower (1976), who used the same water immersion protocol as Cabanac (1971) to evaluate the hedonic characteristics of various stimuli applied to the subjects' hands. The results are shown in Figure 1. Ratings of thermal pleasantness were clearly dependent upon the disposition of thermal stimuli in relation to the overall thermophysiological state of the subject. Positive pleasure was experienced in either hypo- or hyperthermic conditions when the temperature of the applied stimulus was opposite to the thermophysiological state of the subject. Ratings of the magnitude of thermal pleasure were a function of the corrective potential of the stimuli to offset the incurred physiological load-error. For example, applying cool stimuli (27°C) to the hand of hyperthermic subjects elicited a 'pleasant' vote but the coldest stimuli (21°C) rated close to 'very pleasant'.

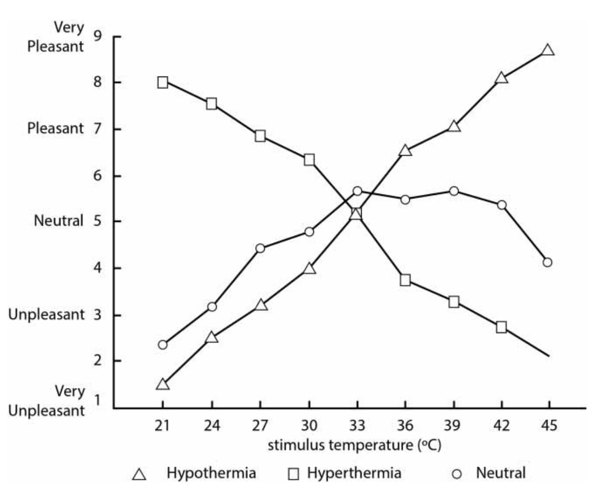

Figure 1 Hedonic character (*y*-axis) of thermal stimuli (*x*-axis) applied to the hands of hypothermic, hyperthermic and thermoneutral subjects (modified after Mower, 1976)

International standards that define thermal comfort in uniform environments such as ISO 7730 (2005) and ASHRAE Standard 55 (2013) are based on the steady-state heat balance equation, as conceptualized by Fanger (1970), that posits 'neutrality', *i.e.* an absence of any thermal sensation, as optimal occupant comfort state for which environments are designed. The simple results from experiments such as Mower's (in Figure 1) clearly show that positive alliesthesia (thermal pleasure) is unattainable in environments where the body is in a neutral, steady-state heat balance with its environment. Indeed, both the alliesthesial model and Fanger's steady-state PMV/PPD model predict that exposure to any peripheral thermal stimuli, warm or cool, for human subjects whose overall thermal state is 'neutral' would be negatively perceived. On the steady-state side of the discussion there is a comprehensive body of experimental support for the view that has defined the themes of thermal comfort research for the past few decades (de Dear et al., 2013). Extensive experimentation with local discomfort, increased air movement and draught risk, and thermal comfort in transitional and non-uniform environments – all which will be detailed below – have brought the legal requirements and occupant expectations of indoor thermal environments to such a tight control range that passive design techniques are practically no longer adequate for the provision of comfort in any climate zone. The thermal comfort literature is replete with lamentations about the displacement of vernaculars and bioclimatic design by technological solutions (*e.g.* Heschong, 1979; Pallasmaa, 2013; Stoops, 2006) wholly reliant on energy intensive mechanical systems.

Running against this trend in the last two decades is the adaptive comfort model (*e.g.* de Dear et al., 2013; de Dear & Brager, 1998; Nicol & Humphreys, 1973) and associated standards (ASHRAE, 2013; EN15251, 2007). The relevance of adaptive comfort standards to the current discussion is that they define boundaries to the 'comfort zone,' sitting somewhere between physiological neutrality and hyperthermia on the warm side, and hypothermia on the cool side.

The research literature on thermal alliesthesia to date has been confined to exposures fixed in specific points in space, often as instances of hyper/hypothermia or neutrality (*e.g.* the immersion protocols used by Cabanac or Mower). But thinking of physiological dynamics encountered within built environments suggests a Lagrangian frame of reference in which the subject experiences a palette of microclimatic exposures as they move about their daily activities. Consider, for example, a person's journey to work. Their thermal trajectory begins in the personally controlled home environment, which is followed by a short-term exposure to suburban microclimate, followed by a complex sequence of diverse exposures on a public transport system, followed by another series of brief and diverse exposures as they walk through variegated urban microclimates. They then enter the vestibule space of their building that serves as a transitional buffer between indoors and outdoors, and then finally they arrive at their workstation which is typically somewhere in a large expanse of an open-plan office where, over the next few hours, they will probably reach steady-state thermal balance to an air-conditioned indoor climate. The trajectory represents a complex sequence of distinctive and sometimes abruptly transitioning microclimatic exposures. These spatial dynamics are further complicated by surges and lulls in internal metabolic heat loads. Both external and internal heat load fluctuations can potentially displace core temperature. A conceptual model of pleasantness based on physiological responses in transient environments has already been proposed by Kuno, Ohno, and Nakahara (1987) and Kuno (1995) that compliments the hypothesis of alliesthesia for dynamic exposures.

The cumulated duration of transient or Lagrangian microclimatic exposures within built environments is relatively minor compared to long-term steady-state exposures at single points in space. For example, the typical office worker is seated stationary at their desk for much longer than they are on the move during the typical day at the office. If the workplace is centrally conditioned to achieve a constant, neutral temperature then the steady-state comfort model (PMV/PPD) may be more appropriate than alliesthesia. But an alternative approach is to follow the adaptive model to establish a range of acceptable indoor temperatures moderated by personal control or augmented by mechanical systems (*e.g.* Zhang et al., 2010d). The concept of positive alliesthesia encourages the deliberate introduction of temperature drifts, air movement, and thermal asymmetries; it precludes an isothermal, steady-state heat balance approach, and requires a fundamentally new understanding of thermal perceptual processes. Alliesthesia potentially presents a unifying framework for understanding thermal perception in non-steady-state indoor thermal environments. The relevance of alliesthesia to the built environment has been defined by de Dear (2011), so the aim of the current paper is to clarify the physiological mechanisms responsible for 'the pleasure principle.'

Thermophysiology of alliesthesia

Skin and core temperatures have long been acknowledged as key physiological correlates of thermal comfort and sensation across the full range of metabolic heat loads (*e.g.* Benzinger, 1979; Gagge, Stolwijk, & Hardy, 1967; Gagge, Stolwijk, & Saltin, 1969; Winslow, Herrington, & Gagge, 1937). The key analytical strategy for disentangling the relative importance of skin and core temperatures in previous investigations into positive thermal alliesthesia (pleasantness) typically involved holding constant ('clamping') one or the other body temperature at levels above, below or very near the predetermined neutral set-point while the other is forced up or down (*e.g.* Winslow et al., 1937; Chatonnet & Cabanac, 1965; Cabanac, Massonnet, & Belaiche, 1972; Mower, 1976; Attia & Engel, 1981). What has been revealed is that the affective component (pleasure or displeasure) of an alliesthesial response to environmental thermal stimuli is formed in reference to a thermoregulatory load-error signal, assumed to emanate from the body core (Cabanac, 1971). This is based on the assumption that there is a single controller responsible for defending the set-point temperature wholly derived from the body core, but this assumption is not entirely consistent with contemporary thermophysiological thinking.

Set-point control

The notion of load-error in cybernetics is premised on the existence of a reference value or set-point for the controlled variable, and this concept has dominated thermophysiological thought for most of last century. The classic textbook depiction of human thermoregulation has a single controller located in the hypothalamus that is responsible for integrating signals from different temperature sensors distributed throughout the body, and then comparing them against a reference or set-point to produce a load-error output to which thermoeffectors respond. This unified thermoregulatory system acts to defend the regulated variable – assumed to be hypothalamic temperature – from environmental or metabolic heat load perturbation. Yet despite the enormous research effort addressing the fundamental question of temperature regulation over the last half century (*e.g.* Hardy, 1961; Hammel, Jackson, Stolwijk, Hardy, & Stromme, 1963; Benzinger, 1969) there is still no concrete proof of the existence of a neuroanatomical structure capable of providing the precise control required by the set-point theory (Werner, Mekjavic, & Taylor, 2008).

Research in recent decades has generated compelling empirical evidence that fundamentally challenges the control theory orthodoxy described above. While beyond the scope of this paper to review the debate (see reviews by Werner, 1980; Romanovsky, 2007), what can be said is that the concept of a single controller is no longer consistent with experimental evidence (*e.g.* Mekjavic, Sundberg, & Linnarsson, 1991; Hensel, 1981). The contemporary view is that our thermoregulatory system comprises multiple controllers that achieve proportional control through separate thermoeffector loops (Satinoff, 1978; Romanovsky, 2007; Werner et al., 2008; Kanosue, Crawshaw, Nagashima, & Yoda, 2010). Each controller is responsible for the activity of a particular thermoeffector, and as body temperature changes they are selectively initiated or deactivated in a coordinated response that is commensurate with the heat-balance perturbation.

This theoretical model of multiple thermoeffector loops operating within a common environment is schematically illustrated in Figure 2. A central temperature range associated with limited autonomic regulatory activity is designated as the thermoneutral zone – also referred to as a dead-band, null zone or interthreshold zone – where vasomotor tone is responsible for fine-detail regulation of heat loss in day-to-day exposures. Body temperature may fluctuate within the thresholds of vasomotor regulation without initiating stronger thermoeffector actions such as shivering or sweating, but once body temperature strays outside the thermoneutral boundaries in Figure 2, then other thermoregulatory loops will be triggered, shivering on the cool side or sweating on the warm. While multiple thermoeffector loops may be less effective than the single controller model at maintaining an invariant body temperature, they can manage a more granular, strategic response that minimizes the need for regulatory remediation, thereby conserving resources.

Whilst this topic may appear to be the domain of physiologists, control theory is deeply embedded in thermal comfort research through the widespread acknowledgement of the crucial role played by subjective thermal perceptions within a behavioural thermoregulatory system. Thermoregulatory behaviour has been conventionally understood as being initiated from signals within the central nervous system, and conscious experiences of discomfort are widely assumed to play that role. The centrality of control theory in our understanding of thermal comfort was cemented by the numerical thermoregulatory model of Stolwijk (1971). The classic two-node comfort model (Gagge, Nishi, & Gonzalez, 1972) and its more recent extensions, multi-node models by Tanabe, Kobayashi, Nakano, Ozeki, and Konishi (2002), Fiala, Lomas and Stohrer (1999), and Huizenga, Hui, and Arens (2001), were all derived from Stolwijk's seminal model. In all these models there persists the explicit assumption of invariant set-point temperature against which the load-error signal is calculated in order to scale the magnitude of a single thermoeffector response.

Load-error signal

The concept of multiple controllers has been refined even further in recent years; it is now believed that the multiple effector thresholds may adjust depending on the changes made by other regulatory actions (Romanovsky, 2007). Coordination between the different controller loops is achieved by them sharing a common regulated variable (Cheng et al., 1995). In effect multiple output signals come from different controllers acting as integrators and comparators of sensory inputs. Body temperature is still widely acknowledged as the regulated variable, shared by all controllers (Kanosue et al., 2010), and is commonly expressed as a weighted average of core and skin

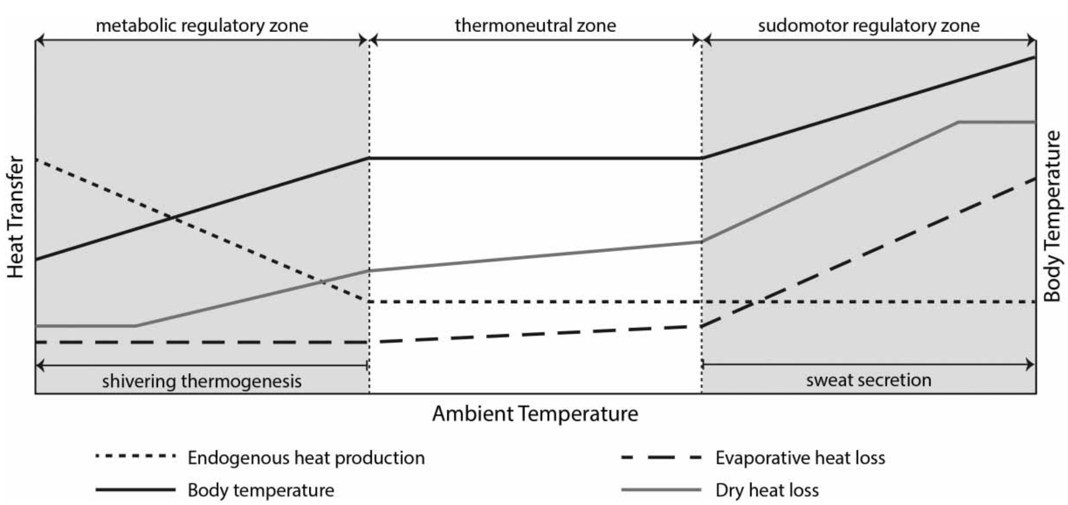

Figure 2 Theoretical model of thermoregulatory actions across different ambient temperatures. Idealized vectors of heat generation and transfer within the physiological system are shown. The vertical dashed lines mark thermoeffector thresholds and shaded areas mark the zones either side of thermoneutral (modified after Werner et al., 2008)

temperatures (*e.g.* Cheng et al., 1995; Frank, Raja, Bulcao, & Goldstein, 1999; Cotter & Taylor, 2005).

In the earliest publications on the alliesthesial model it was presumed that the load-error signal was entirely central in origin. For example, Cabanac's (1971) pioneering work indicated that the deviation in core temperature from a set-point was an appropriate driver of alliesthesia and this simplifying assumption was retained in the most recent discussions of alliesthesia in the thermal comfort literature (de Dear, 2011). However significant research attention aimed at defining the relative contributions of skin and core temperatures to autonomic responses (Cheng et al., 1995; Cotter & Taylor, 2005; Crawshaw, Nadel, Stolwijk, & Stamford, 1975; Gagge et al., 1969; Nadel, Horvath, Dawson, & Tucker, 1970; Nadel, Mitchell, Saltin, & Stolwijk, 1971; Saltin, Gagge, & Stolwijk, 1970; Simon, Pierau, & Taylor, 1986; Wyss, Brengelmann, Johnson, Rowell, & Niederberger, 1974) as well as thermal perception and behavioural thermoregulation (Flouris & Cheung, 2009; Frank et al., 1999; Gagge et al., 1967; Marks & Gonzalez, 1974; Goto, Toftum, de Dear, & Fanger, 2006; Mower, 1976; Schlader, Prange, & Mickleborough, 2009) suggests that the thermoafferent inputs to drive autonomic or perceptual responses may change, depending on body temperature status. Whilst the neural pathways involved in the processing and weighting of converging sensory inputs is yet to be determined, it seems likely that individual controllers generate their load-error signals based on feedback from sensors distributed throughout the entire body (Boulant, 2000; Gordon & Heath, 1986; Nakamura & Morrison, 2008). Relevant to the discussion of alliesthesia is the emerging consensus that peripheral inputs dominate while body temperatures fall within the thresholds of the thermoneutral range in Figure 2.

Misconceptions in thermal comfort research circles that (1) there exists a single controller and (2) that thermoregulatory load-error emanated exclusively from core temperature deviations from a fixed set-point, go some ways toward explaining why the alliesthesial model of thermal comfort has been largely ignored by the built-environment research community. If alliesthesia relied on core temperature being displaced from set-point, then by logical extension, significant discomfort must be a necessary precondition for thermal pleasure. But if the controller responsible for vasoregulation during innocuous thermal environmental exposures (the vast majority of indoor environments) scales the effector magnitude predominantly on the basis of peripheral, not core signals, then the 'displeasure before pleasure' logic is no longer relevant. Moderate thermal sensations resulting from minor fluctuations in skin temperature could potentially generate a sufficient load-error for alliesthesia. Heavier reliance on skin rather than core temperature affords the alliesthesial concept much greater relevance to thermal perception in quotidian, built environmental contexts. The cutaneous alliesthesia hypothesis lends itself to interpretations of non-steady-state environments where regional differences in skin temperature created under dynamic or asymmetric, non-isothermal conditions, could elicit conscious experiences of thermal pleasure, or local thermal discomforts (*e.g.* Arens, Zhang, & Huizenga, 2006a, 2006b; Melikov & Nielsen, 1989; Wyon, Larsson, & Forsgren, 1989).

Spatial alliesthesia

The notion that thermal pleasure, or indeed, thermal displeasure, can only be experienced during core temperature excursions is at odds with lived experience. Moving along our daily trajectories we experience sequences of whole-body thermal pleasures and displeasure, in a rich tapestry of thermal textures: a cool breeze during a balmy summer afternoon, dappled morning sun on a crisp spring morning, transitioning from one hermetically sealed, fully air-conditioned building to another. The alliesthesia in these scenarios is not confined to whole-body experiences; it can be topically administered as well. For example, we commonly derive simple pleasure from wrapping cool hands around a warm mug, or the contrast of a chilled metal balustrade under the palm of our hand as we ascend a staircase. These subtle experiences occur routinely as we move around the built environment without ever disturbing core temperature; the alliesthesia seemingly derived from rapid changes in local skin temperature, contrapuntal to 'global' or whole-body skin temperature. In this taxonomy of thermal hedonics the present authors refer to this as spatial alliesthesia, a perceptual process driven predominantly by cutaneous signals, and different from the more conventional, whole-body model of alliesthesia driven from load errors of central origin. The locus of spatial alliesthesia within the outer body shell clearly points to cutaneous thermoreceptor activity, therefore a brief discussion of peripheral sensors is appropriate.

Cutaneous thermoreceptors

Skin represents the interface between the organism and its environment. As such it is a bellwether, constantly updating us about our immediate microclimatic environment with data from peripheral thermosensitive structures known as cutaneous thermoreceptors. They are unevenly distributed spatially across the body surface and intracutaneously as well. It is generally accepted that cold thermoreceptors are more sensitive than their warm counterparts because they are located more superficially in skin tissue (Ivanov, Konstantinov, Danilova, Sleptchuck, & Rumiantsev, 1986) and according to Hensel (1981) have a larger dynamic coefficient, *i.e.* they generate more frequent impulses for a given temperature transient than do warm receptors for the same but opposite direction temperature transient. The biological significance of heightened cold sensitivity has been discussed elsewhere (*e.g.* de Dear, Ring, & Fanger, 1993; Hensel, 1981; Romanovsky, 2007). Sites with a higher density of thermoreceptors such as the forehead generate stronger thermoafferents than areally larger sites such as the trunk, but do not necessarily exert a greater influence on the triggering of thermoeffector responses (Cotter & Taylor, 2005). Observed areal differentiation of thermal sensitivity, as depicted in Figure 3, is not based solely on thermoreceptor density (Arens et al. 2006a, 2006b; Cotter, Zeyl, Keizer, & Taylor, 1996; Crawshaw et al., 1975; Hensel, 1981; Nadel et al., 1971; Stevens, Marks, & Simonson, 1974; Zhang, Arens, Huizenga, & Han, 2010a, 2010b); higher-order processing by the central nervous system is also implicated (Gordon & Heath, 1986; Nakamura et al., 2008).

Neural firing rates by cutaneous thermoreceptors demonstrate both static and dynamic components, the latter being highly sensitive to changes in local skin temperature (de Dear et al., 1993; Hensel, 1981). Within the thermoneutral zone, thermal perception has been clearly demonstrated to be strongly related to the rate of change of skin temperature with respect to time (*e.g.* Attia & Engel, 1981; Marks & Gonzalez, 1974; Rohles, 1981). Stronger thermal sensations are consistently reported at the immediate onset of ambient temperature step-change stimuli (de Dear et al., 1993) and also ambient temperature cycles (Kingma, Schellen, Frijns, & van Marken Lichtenbelt, 2012), suggesting that the dynamic response of cutaneous thermoreceptors is the key drivers for the perception of sudden change in the thermal environment (Figure 4). To make sense of these common observations several comfort researchers have proposed a feed-forward framework based on peripheral stimulation (Attia & Engel, 1981; Hensel, 1981; Gagge et al., 1967; Kanosue et al., 2010; Marks & Gonzalez, 1974) and this may afford a neurophysiological basis for spatial alliesthesia.

In the language of cybernetics, a control system with feed-forward capability is able to anticipate the

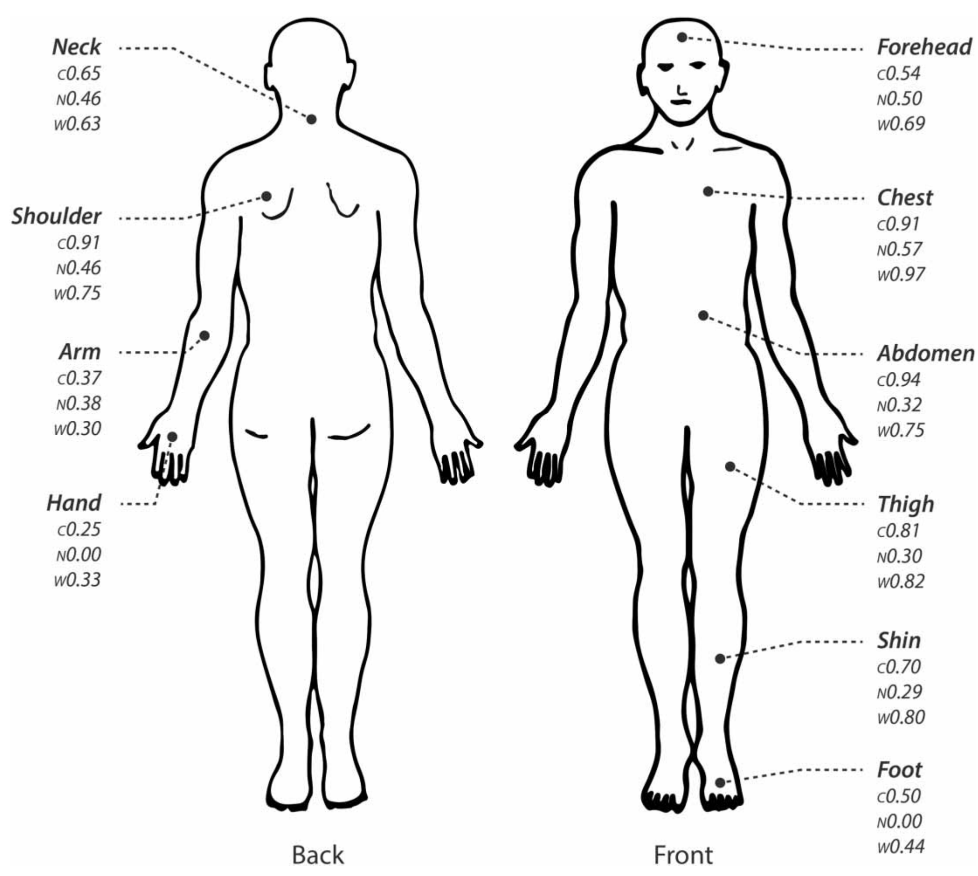

Figure 3 Weighting coefficients of body sites regularly used to measure skin temperature for the 'opposite-sensation model' (Zhang et al., 2010c). Numbers indicate the influence of that site on overall sensation and were determined by piecewise regression for Cool local sensation votes of < -2 (marked as C), Neutral local sensation votes (marked by N) and Warm local sensation votes of > 2 (marked as W)

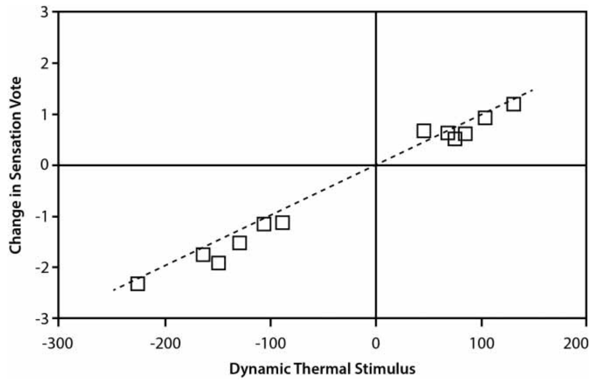

Figure 4 Group mean change in whole-body thermal sensation votes of 12 subjects undergoing ambient temperature step changes as a function of numerically modelled cutaneous thermoreceptor dynamic outputs (after de Dear et al., 1993). Dynamic thermal stimulus (DTS) is receptor output integrated through a 20-second interval post-ambient temperature change, and both temperature step-down (negative DTS units) and temperature step-up (positive DTS units) are shown

effects of change and take steps to pre-empt significant perturbation of the regulated variable. It averts the necessity for more demanding response actions that would be required if control relied solely on feedback from gross displacements of the controlled variable. In our discussion of contemporary thermophysiology theory above it was noted that prioritizing multiple thermoeffector loops forestalled the initiation of metabolically more demanding autonomic thermoeffector actions. Superimposing a feed-forward thermal perception loop (based on skin thermoreceptor signals) onto this system of multiple thermoeffector loops holds teleological appeal given that the skin surface is best placed for the early detection of changing environmental conditions. Neurological evidence (Flouris, 2010; Nakamura & Morrison, 2008; Romanovsky, 2007; Rolls, Grabenhorst, & Parris, 2008) and affective psychology theory (Panksepp, 1998; Rozin, 2003) agree that the central nervous system may use rate sensitivities from thermoreceptors to anticipate the impact of an exposure on body temperature and initiate effector actions in an anticipatory manner. The notion of anticipatory responses within the spatial alliesthesial framework of behavioural thermoregulation affords a coherent explanation of the commonly observed perceptual 'overshoot' during temperature step-changes (*e.g.* Arens et al., 2006a, 2006b; de Dear et al., 1993).

The experimental results from Zhang et al. (2010a, 2010b, 2010c) used to develop a multi-node (*i.e.* anatomically disaggregated) thermal comfort model also affords empirical support for the notion of spatial alliesthesia in asymmetric or non-isothermal environments. First, physiological inputs to their predictive model included a time-derivative of local skin temperature as well as the change in whole-body skin temperature from its comfort set-point (defined empirically as the temperature corresponding to a neutral thermal sensation vote). These parameters may be considered to represent the local dynamic response and the global steady-state response of thermoreceptors respectively, and in combination represent the likely neurophysiological inputs to an alliesthesial interpretation of the counterpoint between local and global skin stimuli. Second, the Zhang et al. (2010a, 2010b, 2010c) algorithm for predicting change in global (whole-body) thermal sensation from combined sensory inputs of specific body parts during asymmetrical conditions ('opposite-sensation model') heavily weighted those sites with local thermal sensation votes opposing the whole-body status. Under conditions of significantly perturbed local skin temperature but only minor change in whole-body mean skin temperature, whole-body perception was observed to be mainly influenced by the body site with the anomalous thermal sensation. Recasting these observations within the spatial alliesthesial framework, a local skin temperature disturbance triggers the dynamic response of cutaneous thermoreceptors at that site and the resulting thermoafferent traffic displaces whole-body thermal perceptions away from comfort or neutrality – an unpleasant local thermal experience. It seems reasonable to extrapolate this logic to the opposite scenario in which the localized stimulation is corrective because global skin temperature has already been displaced from neutrality or comfort. The spatial alliesthesia hypothesis being developed in this paper predicts thermal pleasure under such a scenario.

Reinterpreting the 'classic' thermal discomforts in terms of alliesthesia

The original, whole-body alliesthesia concept (Cabanac, 1971; de Dear, 2011) is understood to be driven by the contrast between core and skin temperature trends, and as such, well suited to understanding transient or non-steady-state comfort problems, such as transitional or vestibular spaces (Hensen, 1990). But for reasons outlined earlier in this paper, reliance on displacement of core temperature renders the temporal variant of alliesthesia impractical as a design principle for steady-state scenarios in which the subjects (occupants) are sedentary. However the spatial alliesthesia hypothesis developed in this paper shifts the locus towards thermoreceptors embedded in the skin and in so doing, enlarges the scope of applicability to more conventional indoor thermal comfort problems which almost always fall within the innocuous region of the physiologically thermoneutral zone in Figure 2. The remainder of this paper uses the alliesthesia hypothesis as a common thread that ties together seemingly disparate bodies of thermal comfort observational data. It also integrates hitherto disconnected sections of the ASHRAE Standard 55 (ASHRAE, 2010, 2013) into a coherent explanation of thermal perception under non-isothermal and non-steady-state environmental conditions.

Elevated air speed

The research topic of air movement impacts on thermal comfort (*e.g.* Toftum, 2004) represents the intersection of adaptive comfort concepts and thermal alliesthesia within the built environment. Much of the research on air movement and indoor thermal comfort has focused on the unwanted localized cooling associated with the sensation of draught (*e.g.* Fanger et al., 1985; Melikov & Nielsen, 1989), particularly in the context of personally controlled air movement (Kaczmarczyk, Melikov, & Fanger, 2004; Melikov, Cermak, & Majer, 2002) for thermally neutral occupants. While those researchers may not have stated it directly their research premise is essentially what we have defined as negative thermal alliesthesia in the current paper. For subjects experiencing mildly warmer-than-neutral whole-body sensations, air movement represents a desirable and sustainable mode of cooling (*e.g.* Bauman, Carter, & Baughman, 1998; Hoyt, Zhang, & Arens, 2009; Toftum, 2004). This has been repeatedly noted in warm or tropical climate zones (*e.g.* Cândido, de Dear, Lamberts, & Bittencourt, 2010; Tanabe & Kimura, 1994) where natural ventilation, ceiling or personal fans can dissipate convective and latent body heat, forestalling occupant demands for more energy intensive compressor-based air-conditioning. While the alliesthesial explanation of thermal perception may not have been explicitly invoked in that literature, the positive hedonic tone potentially associated with elevated air movement in buildings has long been recognized, and was formalized in a recent revision to the ASHRAE's Standard 55-2013. In that document air speeds within the occupied zone up to 1.2 m/s are now sanctioned in ambient temperatures above 27.5°C in contexts where personal control is available to the building occupant, and clothing level is around 0.5 clo and metabolic rate is < 1.3 met.

Steady-state exposures to isothermal environments in which subjects express neutral or preferred thermal sensations, as was the case for experiments underpinning the draught risk model (Fanger et al., 1985; Melikov et al., 2002), would render localized air movement stimuli unpleasant due to the absence of a thermoregulatory imbalance under those conditions. However, the same rates of air movement applied on the warm side of the comfort zone (*i.e.* acceptably warm conditions) would carry a positive hedonic tone due to the corrective role of skin heat loss in offsetting the regulatory heat surplus caused by such exposures. The perceptual processes leading to the classification of air movement as either unpleasant draught (negative valence) or pleasant breeze (positive valence) are grounded in the underlying physiological state and as such, appropriately accommodated within the alliesthesial framework.

While they may not have used the term, Tanabe and Kimuras' (1989, 1994) study into the effects of air movement patterns on thermal perception represents a clear illustration of the alliesthesial hypothesis. For example, subjects exposed to Tanabe and Kimura's 29°C experiment conditions (RH = 50%) had about the same mean skin temperature under sinusoidally fluctuating air movement (at periods of 10, 30 and 60 s) and under a constant airflow: 34.2 and 34.4°C respectively. Despite identical mean air speeds (approximately 1.0 m/s) and very similar skin temperatures under the different airflow patterns, subjects reported a lower thermal sensation vote during the sinusoidally fluctuating airflow (-0.41) compared to constant air movement (0.32). That discrepancy of about two-thirds of a thermal sensation vote would equate approximately to two degrees of operative temperature effect, so the sinusoidal effect is non-trivial. The same perceptual response pattern was observed by Zhou, Ouyang, Lin, and Zhu (2006) in their investigation of thermal sensation during different velocity fluctuation patterns. Translating these experimental findings into the alliesthesia hypothesis, oscillating skin temperatures resulting from convective heat loss under sinusoidal air movement would elicit a greater number of neuron discharges from cold cutaneous thermoreceptors during the air speed accelerations than from the warm receptors during the air speed decelerations, simply because of the relative proximity of cold receptors to skin surface compared to the warm counterparts (Hensel, 1981). The large volume of thermoafferent traffic would generated a more perceptible cool sensation compared to the decayed response when exposed to a constant air speed, despite the mean airspeed and ambient temperature being the same under both conditions. The subjects in the Tanabe and Kimura (1994) experiment would have found the localized cooling caused by airflow a pleasant contrast to the warm global condition – in effect they were enjoying spatial alliesthesia.

Temperature ramps and cycles

In its performance specification for comfort in dynamic environments ASHRAE's thermal comfort Standard 55 (ASHRAE, 2013) contains specific requirements for cyclical variations or ramps in operative temperature. The limiting criteria were informed by classic laboratory studies of thermal comfort under transient exposures (Rohles, Milliken, Skipton, & Krstic, 1980; Sprague & McNall, 1970; Wyon, Andersen, & Lundqvist, 1972). Despite experimental design differences in peak-to-peak amplitudes and cyclical frequencies or ramp speeds, there was a consensus that near-sedentary subjects would experience discomfort if their operative temperature strayed outside the steady-state comfort zone for longer than an hour. In a thorough review of the early transient thermal comfort literature, Hensen (1990) argued that experimental results supported a 2.2 K/h restriction for cyclical variations in operative temperature. He also argued that the limiting rates of change for temperature drifts or ramping protocols should be similar. The purpose of such limits is to prevent occupants experiencing discomfort, but this approach is obviously inconsistent with the literature on elevated air movement in the upper range of the adaptive comfort zone (the preceding section of this paper). The rates of change in skin temperature resulting from mechanically driven air velocity fluctuations (*e.g.* Houghten, Gutberlet, & Witkowski, 1938) and the turbulent gusts and lulls embedded in spaces with natural ventilation far exceed those associated with allowable temperature cycles/drifts (*e.g.* Rohles et al. 1980), so this begs the question, why do they lead to thermal pleasure in one context but thermal discomfort during cycles/drifts in operative temperature?

These differences would certainly elicit different outputs from cutaneous thermoreceptors; ambient temperatures drifting slower than 2.2 K/hour would activate the static (steady-state) thermoreceptor response, but the more profound dynamic sensitivity of thermoreceptors would remain dormant under such slow transients. In effect subjective perceptions of these environments would be indistinguishable from the steady-state skin temperature functions contained in classical thermal comfort theory, and discomfort could be expected during prolonged excursions beyond the normal steady-state comfort limits. In contrast, the turbulence embedded in naturally ventilated air flow regimes should produce skin temperature fluctuations fast enough to excite the dynamic thermoreceptor response in skin sites directly exposed, and if the dynamic convective cooling were superimposed on warmer-than-preferred temperatures, the requirements for positive spatial alliesthesia would be obtained – a case of thermal counterpoint.

Local thermal discomfort

Local skin temperatures are naturally inhomogeneous, with head-to-toe gradients of up to 4 K not uncommon even in steady-state (Candas, 2005). This difference can widen in non-uniform and non-steady-state environments due to uneven distribution of clothing or complex exposures of the body surface to temperature transients, thermal and radiant asymmetries, or personal comfort systems (Wyon et al., 1989). ASHRAE's thermal comfort Standard 55 (ASHRAE, 2013) contains prescriptions aimed at minimizing the temperature differences between the normal body trunk and distal areas. Specific local discomforts regulated in the standard include vertical air temperature stratification between the feet and the head, asymmetric radiant field enveloping the body, localized and unwanted convective cooling (draught), and direct contact with heated or cooled surfaces. The standard's acceptable limits are based on extensive climate chamber studies involving human subjects being exposed to the sources of local discomfort while casting subjective comfort and acceptability evaluations on questionnaires. However, all of these studies (*e.g.* Fanger et al., 1985; McIntyre & Griffiths, 1972; Melikov & Nielsen, 1989; Olesen, 1977a, 1977b) were designed to highlight negative rather than positive alliesthesia – indeed the whole subfield of research is usually classified as 'local discomfort' and the application of such research is in heating, ventilation and air-conditioning (HVAC) engineering where the goal is typically construed as dissatisfaction minimization:

- *Radiant temperature asymmetry*
  Designed to prevent discomfort resulting from exposure to the radiant field emanating from hot or cold surfaces such as heated ceilings or direct sunlight in buildings. Based largely on classic studies by Fanger, Banhidi, Olesen, & Langkilde (1980) who exposed subjects to increasing radiant temperatures overhead whilst decreasing air temperature to maintain the same operative temperature. The source of discomfort was attributed equally to the head (uncomfortably warm) and the feet (uncomfortably cool) following the widening of the temperature gradient along the cephalo-caudal axis. The asymmetry tested by Fanger et al. (represented hypothetically in Figure 5) diverges from the 'ideal profile' or 'piste' proposed by Wyon et al. (1989) in experiments on vehicle cabin climates (Figure 5) and summarized in the familiar aphorism 'cool-head and warm-feet'. It is conceivable that if the gradient were reversed from that plotted in Figure 5, for example by radiant cooling from the ceiling and floor heating under foot, the hedonic valence would also reverse, because the requirements for positive alliesthesia have been met.

- *Draught*
  Unwanted local cooling, or draught, is frequently cited as the most common complaint in office buildings, particularly in buildings located in cold climates. Extensive experimentation on draught dissatisfaction (see Toftum, 2004 for a review) following the introduction of the draught risk (DR) model by Fanger and Christensen (1986) has quantified how convective cooling is negatively perceived when global thermal

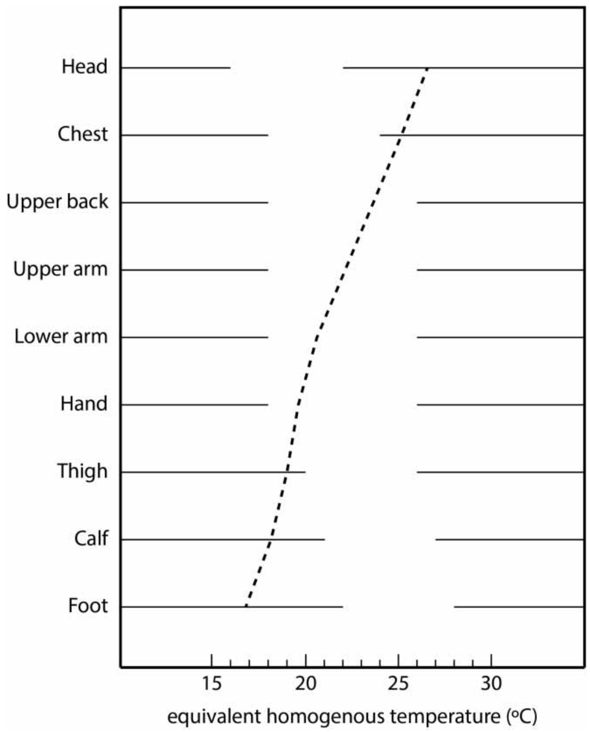

Figure 5 Hypothetical profile of equivalent homogenous temperatures (EHT) that might have resulted from Fanger, Banhidi, Olesen, & Langkilde's (1980) overhead radiant asymmetry experiments overlain by Wyon's 'piste' of ideal comfort EHT

sensation is below neutral and this body of experimental research forms the empirical basis of draught guidelines (ISO, 2005). More recent research including both laboratory studies (*e.g.* Tanabe & Kimura, 1994; Zhou et al., 2006) and field research (*e.g.* Aynsley, 2008; Cândido et al., 2010; Hoyt et al., 2009) have demonstrated the positive perceptual response associated with increased air movement inside buildings when occupants' general thermal state is slightly warm but still within the warm limit of the adaptive comfort zone. According to the alliesthesial hypothesis, the crucial factor that determines whether a given regime of air movement will be perceived as unwanted draught, or desirable breeze, is the general thermal status of the subject, but to date this has been largely overlooked in the thermal comfort standards, particularly ISO 7730 (2005).

- *Vertical air temperature difference*
  Less well documented than the other sources of local discomfort, the standards on vertical temperature stratification (ASHRAE, 2013; ISO, 2005) are based largely on experimental research by Olesen, Scholer, & Fanger (1979). A sample of 16 subjects were exposed to four different vertically stratified indoor atmospheres with temperature gradients from head to feet of 0.4, 2.5, 5 and 7.5 K (warmer being at head height). As in the earlier research results of Fanger et al. (1980) and reported in the preceding discussion of radiant asymmetry, the source of steady-state discomfort from vertical temperature differences stems from warm discomfort of the head and cold discomfort of the feet. Essentially the natural buoyancy forces operating in room air leading to thermal stratification run counter to Wyon et al.'s (1989) idealized comfort 'piste', summarized as 'cool-head and warm-feet'. In the parlance of alliesthesia, natural thermal stratification prompts negative alliesthesia. However an inversion of thermal stratification by cooling from overhead and warming from underneath could potentially provide thermal pleasure due to regional differences in thermal sensitivity along the body's cephalo-caudal axis.

- *Floor surface temperature*
  This part of the comfort standards addresses local discomfort resulting from contact with floor surfaces that are too warm or too cool. Based on work by Olesen (1977a) who exposed a small sample ($n = 16$) of thermally neutral, sedentary subjects to floors of differing surface temperatures. The ambient temperature during exposure was selected according to each subject's preference. These results were synthesized with pre-existing data from other authors (Olesen, 1977b) to arrive at the recommended floor temperatures for shoed feet. A predicted percentage dissatisfied (PPD) function was fitted to the sample's foot comfort responses to floor temperatures by regression techniques. In order to generalize the findings and widen the scope of the PPD curve's applicability, Olesen changed ambient temperatures during the contact heating/cooling exposures two degrees either side of 8 male subjects' preferred temperatures, and concluded that differences in subject's general thermal status had no impact on the generalized PPD curve for contact heating/cooling of feet. The basic findings for subjects in their preferred ambient temperature are perfectly consistent with an alliesthesial interpretation – any heating or cooling of persons in their preferred thermal condition by any mode of heat transfer is very likely to elicit a negative alliesthesial load-error signal which will translate into thermal dissatisfaction. But generalizing this to ambient temperatures that are warmer or cooler than preferred fundamentally contradicts the alliesthesial interpretation of this scenario. Alliesthesia predicts that cool floors would feel positively pleasant to subjects who were in the warmer half of the physiologically thermoneutral

> zone (Figure 2), and vice versa, warm floors would feel positively pleasant to subjects in cooler-than-preferred ambient temperatures. An obvious explanation for Olesen's (1977a, 1977b) results on the non-effect of 'general thermal state' is because the research design shifted ambient temperatures very moderately at ± 2 K around the subject's preferred temperature, and this is likely to be insufficient to shift their 'general thermal state' enough to generate a spatial alliesthesial load-error signal.

In all these experiments the research design was basically the same – subjects sitting in steady-state with their preferred ambient temperature (*i.e.* the centre of the thermoneutral zone in Figure 2) were exposed to a localized thermal perturbation of one sort or another, directed at a specific body site, and then asked to evaluate it subjectively. In essence this is a negative alliesthesia research design, and the local discomfort guidelines in comfort standards like ISO 7730 (2005) and ASHRAE Standard 55 (2013) that are based on these experiments could, technically speaking, have been named 'Guidelines for minimization of negative alliesthesia'. But what is missing in all of them is the positive hedonic dimension of alliesthesia – thermal pleasure. This topic will be the focus of a sequel in this series of papers.

Conclusions

In their analysis of massive open-access databases comprising occupant satisfaction in office buildings around the world, Arens, Humphreys, de Dear, and Zhang (2010) concluded that spaces in buildings with a tighter temperature tolerance (± 0.2 PMV) were unable to achieve higher levels of occupant thermal satisfaction than buildings with not-so-tight thermal regimes. Clearly the concept of a one-size-fits-all approach to the provision of thermal comfort for a given population using centralized mechanical systems is not only undesirable but also fundamentally flawed. Diversity in the thermal preferences of building occupants resulting from variations in clothing level, metabolic activity, expectations, physiology *etc* suggest the criteria for evaluating occupants' thermal acceptability in office buildings may need to be recast. As summarized by de Dear (2011) in the concluding section of an earlier paper in this series on alliesthesia:

> If the very best that can be achieved in an isothermal, cool, dry and still indoor climate is 'neutral' or 'acceptable' for little more than 80% of a building's occupants at any one time, then the standards that have been set to date leave much to be desired.
>
> (p. 115)

Alliesthesia represents a unifying framework for understanding phenomenology of indoor thermal environments. Although extant literature on transient or spatially non-uniform thermal comfort is typically focused on minimization or complete elimination of *dis*comfort, *i.e.* negative alliesthesia, this paper demonstrated that positive pleasure can be associated with temporal thermal transients; in effect the flipside of the same coin called alliesthesia. The hedonic tone of a non-steady-state thermal environment is not intrinsic to the physical environmental conditions *per se*, but depends on the thermal physiological state of the subject who is being exposed. It is important to point out that this alliesthesial lens on the thermal environment is not inconsistent with current understanding of perception in steady-state thermal environments. What is missing from the research discourse is a discussion of the potential for non-steady-state indoor thermal environments to lift occupant satisfaction rates within thermally neutral indoor climates above the current optimum of about 80%. At this point it is perhaps premature to propose a systematic and detailed catalogue of design solutions, but some broad generalizations are appropriate. In order to leverage alliesthesial pleasure control must be returned to occupants by embedding adaptive opportunities into the design or fit-out. Personalized environmental control (PEC) capable of creating bespoke environments catering for the expectations and preferences of individual occupants are an obvious implementation of the alliesthesial principle. The energy implications of widening set-point control ranges have been emphasized in recent literature (Hoyt, Arens, & Zhang, 2014) but the positive alliesthesial benefits are yet to be systematically researched.

This paper has elaborated further the neurophysiological basis of thermal alliesthesia. The alliesthesia hypothesis provides an overarching framework within which diverse and previously disconnected findings of laboratory experiments, field studies, and even comfort standards spanning the last 40 years of thermal comfort research can be more fully understood and reconciled. The alliesthesia hypothesis accommodates a large body of knowledge about thermal comfort under steady-state conditions alongside non-steady-state and non-uniform environments. In order to maximize the potential of these dynamic environments to create instances of thermal pleasure, efforts to integrate hedonics into the built environment need to be extended further. This is an exciting idea that requires a significant departure from steady-state models of thermal comfort, but the pleasure principle would open up new avenues of design and engineering solutions that excite the thermal sense to overcome thermal boredom in the built environment.

The next instalments in this series of papers on alliesthesia will provide more focused experimental evidence in support of the alliesthesial framework of thermal perception.

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