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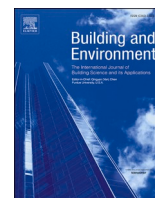
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Dynamic thermal perception: A review and agenda for future experimental research

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ABSTRACT

Buildings could actively participate in the emerging smart electrical grid if they were able to incorporate dynamic modulations of indoor temperature set-points. But the mechanisms of dynamic thermal perception remain relatively poorly understood and we are still far from being able to design and control temperature fluctuations that would be comfortable for occupants. In this paper, we review the current state of knowledge on thermal comfort during non-steady state conditions. We especially focus on the psycho-physiological phenomena of thermal alliesthesia and thermal habituation, both of which are known to affect the dynamic thermal perception but have received scant attention in previous reviews and are yet to be fully characterized. By drawing from experimental literature (1960 through 2021) on thermal comfort under transient conditions and from recent neurophysiological evidence, we identify major knowledge gaps in the domain of dynamic thermal perception and set future research needs required to fill these gaps.

1. Introduction

1.1. Context

Past efforts in thermal comfort research have been mostly dedicated to understand which environmental and physiological conditions lead to thermal comfort under steady-state exposures. This focus on static and isothermal states has been translated in the prescription of fixed set-point temperatures in buildings. Now, the emerging smart grid paradigm calls for a rethink of the way buildings are designed and operated. In contrast to a fixed set-point driven design, the implementation of dynamic modulations of the set-point temperature could facilitate time-shifting and/or shaving buildings' heating and cooling peak demands, and enhance their energy flexibility. Combining this flexibility into the electrical power system could make it feasible to integrate - efficiently and inexpensively - an increasing share of intermittent renewable energy generation. Set-point temperature fluctuations could also help to increase set-point temperatures in summer and lower them in winter and, thus, reduce buildings' heating and cooling energy consumption. Given that the provision of thermal comfort is one of the largest contributors to global energy consumption [1] and that the use of electricity for heating and cooling is growing rapidly [2], the implementation of

comfortable set-point modulations in buildings could significantly support the clean energy transition [3]. However, the psycho-physiology of thermal perception under transient conditions remains relatively poorly understood and, thus, we are still far from being able to design and control dynamic modulations of indoor temperature set-points that would be acceptable, let alone comfortable for occupants.

1.2. State-of-the-art

Thermal perception has two main semantic dimensions: sensation and comfort. Thermal sensation (i.e. feeling warm, neutral, cold, etc.) is regarded as its objective or descriptive dimension and is most often assessed with the ASHRAE seven-point scale [4]. Thermal comfort is the affective or hedonic component of thermal perception and can be assessed in terms other than those properly related to comfort, for example thermal acceptability, thermal preference and/or thermal pleasure [5]. It is also thought that thermal discomfort (and not thermal sensation) is important for activating thermoregulatory behaviours in humans [6]. Purposive thermoregulatory behaviours have been described as “an attempt to avoid what humans call thermal discomfort or displeasure and to obtain thermal pleasure” [7].

In 1981, Rohles described the human sensory response to the thermal

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environment as dependent on seven variables (air temperature, relative humidity, mean radiant temperature, air velocity, physical activity, clothing and time), stressing that “*time has received only modest attention as a variable in comfort research*” [8]. Forty years later, the “*time*” variable persists as the least well understood in the domain of thermal comfort research.

In current thermal standards, indoor temperature variations outside the control of occupants are mostly regarded as something negative which are to be minimised. Accordingly, only indications on the maximum temperature changes allowed over certain periods are given. The ASHRAE Standard 55 sets to 3.3 °C the maximum operative temperature change allowed for ramps or drifts over an exposure of 4 h as long as the variations are within 1.1 °C, 1.7 °C, 2.2 °C, 2.8 °C for each 15 min, 30 min, 1 h, and 2 h respectively [4]. Ramps refer to actively controlled monotonic changes, while drifts are passive (free-running) changes. Cyclical temperature variations (repeated rises and falls of the temperature) with periods longer than 15 min are treated as ramps or drifts. For cyclical variations with periods shorter than 15 min a maximum peak-to-peak variation in operative temperature of 1.1 °C is permitted. The ISO standard 7730 sets a maximum peak-to-peak variation of 1 °C for cyclic variations and recommends steady-state comfort criteria for ramps and drifts when the rate of temperature change is less than 2 °C/h [9].

On the other hand, steady-state comfort prescriptions in the standards are the prerogative of either Fanger’s PMV/PPD model, for mechanically heated and/or cooled buildings, or an adaptive thermal comfort model for free-running buildings. Fanger’s model is derived from a steady-state heat balance analysis of human subjects under long-term (up to 3 h) climate chamber experiments and is, therefore, only suited to predict thermal comfort under steady-state or slowly changing indoor conditions (i.e. temperature gradients less than 2 °C/h) [10]. Furthermore, the model is not able to predict thermal comfort under time-varying levels of activity or changes of clothing insulation. The adaptive thermal comfort models prescribe comfort temperature boundaries within which the indoor temperature can fluctuate [11,12]. Hence, the adaptive models acknowledge people’s adaptation to seasonal temperature variations through various thermal physiological, psychological, and behavioural changes. However, they focus on long-term adaptive processes and, thus, remain silent on how short-term thermal transients affect occupants’ thermal perception.

As an alternative to Fanger’s steady-state heat balance model, more complex multi-segmental and multi-node dynamic models of human thermoregulation have evolved in the past 40 years (e.g. Tanabe [13], Fiala [14,15], the Berkeley Comfort Model [16] and ThermoSEM [17]). These models simulate both the heat transfer within the human body, and between the human body and its environment (“*passive system*”), and the thermoregulatory mechanisms that regulate the internal body temperature (“*active system*”). The anatomical resolution of multi-node models enable them to predict high-resolution skin and body core temperature responses [18]. The predicted physiological state variables can then be coupled to analytical thermal perception models, which are mainly based on regression analyses of experimental thermal sensation and/or comfort observations. Extant literature offers four main physiological-based mathematical models of thermal sensation (the inputs parameters are shown in parenthesis):

- Fiala’s model (ΔT_{core} , $\Delta T_{\text{sk,mean}}$, $\partial T_{\text{sk,mean}}/\partial t$) [19],
- Zhang’s model ($\Delta T_{\text{sk,mean}}$, $\Delta T_{\text{sk,local}}$, $\partial T_{\text{sk,local}}/\partial t$) [20–22],
- Takada’s model ($\Delta T_{\text{sk,mean}}$, $\partial T_{\text{sk,mean}}/\partial t$) [23],
- Kingma’s model ($T_{\text{sk,mean}}$, $\partial T_{\text{sk,mean}}/\partial t$) [17].

where ΔT_{core} , $\Delta T_{\text{sk,mean}}$, and $\Delta T_{\text{sk,local}}$ are the differences between the body core, mean skin and local skin temperatures in the actual conditions and their values for thermo-neutral conditions (i.e. the neutral points or thresholds), $\partial T_{\text{sk,mean}}/\partial t$ and $\partial T_{\text{sk,local}}/\partial t$ are the rates of change of the mean and local skin temperatures, respectively.

The Zhang model stands out due to three unique features:

- It formally accounts for the phenomena of thermal alliesthesia and thermal habituation.
- It predicts both whole-body and local thermal sensation under non-isothermal indoor environments.
- It explicitly differentiates thermal comfort from thermal sensation.

These features make Zhang’s model capable of describing many aspects of human thermal perception: for example, how the brain integrates contradictory local thermal sensation signals, and the relationship between thermal sensation and comfort. The empirical basis of Zhang’s model comprised 70 localized cooling experiments (i.e. specific anatomical sites stimulated individually) and eight localized heating exposures. In particular, 67 tests addressed localized cooling in warm ambient environments, three tests addressed localized cooling in cold environments, and eight tests considered localized heating in cold environments. This unique set of experimental data greatly contributed to improving our understanding of thermal comfort under dynamic and non-uniform thermal conditions. However, the majority of the data came from temperature down-steps under warm ambient conditions. No tests addressed localized heating of a warm whole-body and data from cyclical temperature variations were omitted. This limits the scope of the dataset and the predictive capability of Zhang’s model [10].

Despite the significant research efforts already invested in physiologically-based mathematical models of thermal perception, particularly Zhang’s model, there still remains ample scope for their improvement. Various aspects of non-isothermal comfort deserve further attention but the temporal dimension stands out as particularly urgent for applications in the emerging smart grid paradigm. Previous reviews addressing the topic of dynamic thermal comfort include the works of Hensen [24], Zhu [25] and Mishra [26]. Hensen wrote the first literature review on thermal comfort under transient conditions, specifically aimed at identifying acceptable dynamic indoor temperature variations [24]. Zhu focused on the positive thermal comfort impact of airflow dynamics mimicking the turbulent characteristics of natural wind [25]. Mishra’s more recent review comprehensively surveyed thermal comfort studies dealing with spatial and temporal non-uniformities [26].

1.3. Research aims

The purpose of this work is to present a comprehensive review concerning thermal comfort experimental research conducted under non-steady state conditions, in order to: (1) highlight existing knowledge gaps and (2) pinpoint research efforts required to fill these gaps. All reviews to date [24–26] have approached the problem of dynamic thermal perception by relating subjective states directly to objective environmental conditions. In the present review we depart from this conceptual structure by interposing the physiological variables of skin and body core temperature between environment and perception. We believe that this is the best possible pathway to explicitly modelling dynamic thermal perception. Skin temperature represents the most important physiological variable affecting the dynamic thermal perception under the conditions typically encountered in the indoor built environment, which lay within the thermoneutral zone (TNZ) of vasomotor regulation. Under such conditions, characterized by adjustments of skin blood flow (i.e. vasoconstriction and vasodilation), sweating typically does not occur or does occur but in limited amount which implies that the role of factors such as skin wetness, for example, are less important than that of skin temperature. Given this fact, but also due to the still controversial understanding of the molecular basis of human hygro-sensation [27], we have decided to only focus on skin and body core temperature as predictors of dynamic thermal perception. Furthermore, in this review we focus on the two phenomena of thermal alliesthesia and thermal habituation, which are known to affect the

dynamic thermal perception but whose causal influences and consequences are yet to be adequately represented in predictive models.

The paper starts by reviewing the basic processes of thermal perception with particular attention given to thermal alliesthesia and thermal habituation in Section 2. It is followed by a comprehensive review of dynamic thermal comfort in controlled thermal exposures in Section 3. Finally, Section 4 highlights existing gaps in the comprehension of dynamic thermal sensory phenomena and prioritises an agenda for future experimental research.

2. Fundamentals of dynamic thermal perception

In this Section, we review the basics of thermal perception by drawing from recent neurophysiological evidence (Section 2.1). We then focus on the current understanding of thermal alliesthesia (Section 2.2) and thermal habituation (Section 2.3), highlighting their important role in mediating the dynamic thermal sensory response.

2.1. Pathways for thermal perception

Thermal perception begins with the activation of *primary sensory neurons*, whose role is to convert thermal stimuli into pulses of electrical discharge, commonly described as “*firing rate*”, which then travel to second-order neurons, where they are further processed before being transmitted to the *central nervous system* (CNS) [28,29]. This path is shown in Fig. 1. Primary sensory neurons each comprise a cell body and two branches: one ending in *molecular temperature sensors* located in peripheral and visceral tissues and the other placed in different layers of the dorsal horn of the spinal cord. The cell bodies are situated, for all regions except head and face, in the *dorsal root ganglia* (DRG). In the spinal cord, primary sensory neurons form synapses with different types of *secondary sensory neurons*.

The molecular temperature sensors located in the peripheral tissues are also known as peripheral/cutaneous thermoreceptors, while central/core thermoreceptors are located in the hypothalamus, spinal cord and viscera. The molecular entity of central/core thermoreceptors located within the hypothalamus has not been clearly established yet [28,30]. The molecular temperature sensors of the skin, spinal cord and viscera mostly belong to the family of the relatively recently discovered transient receptor potential (TRP) ion channels [31]. Depending on the type of TRP ion channel that they are expressing, primary sensory neurons can selectively encode heat and cold. In particular, there is a general agreement that TRPM8-expressing primary sensory neurons encode cold. The role of TRPM2 or TRPV1 ion channels is more controversial but they appear to be mainly implicated in the perception of warmth [32]. Few TRPM2-, TRPV1- and TRPM8-neurons encode both heat and

cold. Second-order neurons can also be classified based on their response to cold, heat, and both heat and cold [33]. Thus, the information coming from hot and cold stimuli is registered and transmitted via different categories of sensors characterized by different and relatively narrow thermo-sensitivities that are cumulatively covering a very wide range: from painful heat to noxious cold. They are also characterized by different types of dynamic behaviours [34,35].

The static electrical discharge of primary sensory neurons has a maximum at a certain absolute temperature that varies depending on the temperature sensitivity of the sensor. The dynamic response enables rapid reactions to environmental changes and depends on both the rate of change of the temperature and the absolute temperature. This means that cooling and warming transients elicit different sensory responses at different absolute temperatures. Furthermore, the dynamic behaviour of a warm receptor is characterized by a spiking of the firing rate under sudden warming and by a transient inhibition under sudden cooling, whereas a cold receptor responds in the opposite way, i.e. with an overshoot of the firing rate on cooling and an inhibition on warming [34, 35]. Recent neurophysiological evidence has shown that the perception of innocuous skin warming depends on the inhibition of cold-activated TRPM8-neurons, suggesting that the ability of these cold-encoding neurons to detect the rate of cooling also allows them to sense the rate of warming by inhibition (instead of spiking) of their firing rate [37]. Thus, cold-activated TRPM8-expressing primary sensory neurons are required for the perception of warmth. Furthermore, the response of cold-sensitive spinal neurons has been found to mainly depend on the time-rate of cooling and rapidly adapt to the steady-state value. In contrast, heat-sensitive spinal neurons mainly respond to the absolute temperatures and are not as adaptive [33].

Secondary spinal neurons project to different areas of the CNS including:

- The *preoptic area of the hypothalamus* for the initiation of autonomic thermoregulatory processes (i.e. vasodilation and vasoconstriction, sweating, shivering, etc.) [38].
- The *primary somatosensory cortex* and the *thalamus* for providing an objective assessment of temperature and forming the basis of thermal sensation (i.e. feeling warm, neutral, cold, etc.) [39].
- The *lateral parabrachial nucleus* that is believed to be implicated in the affective or hedonic dimensions of thermal perception, namely comfort and pleasure [40].

Thus, while thermal sensation and thermal comfort both have origins in the CNS, they appear to come from different parts of it, with thermal comfort having more overtly hedonic qualities than thermal sensation [6]. Furthermore, both autonomic and behavioural thermoregulatory actions originate in the CNS but, again, in distinct zones of it.

It has been further shown that skin temperature has a relatively greater contribution to thermal sensation than to autonomic thermoregulation, as compared to body core temperature [38,41]. Furthermore, it has been found that the skin temperature of some body sites exerts a much stronger influence on whole-body thermal sensation than others [20–22,42]. The most influential skin areas are the cheek, back and neck back, abdomen, and pelvis. The main function of these skin areas seems to be registering thermal sensation rather than adjusting heat loss. When these body areas are cooled, the whole-body sensation is predominantly cool, regardless of localised sensations emanating from other skin regions. The least influential skin areas include the hand and foot. Their main function appears to be to adjust internal heat content distribution through vasoconstriction/vasodilation rather than contribute to whole-body thermal sensation. All areas of the head and arms and legs are moderately influential at managing thermal status. Their behaviour falls between the two groups described above. These general patterns are particularly evident during cooling transients [20–22,43].

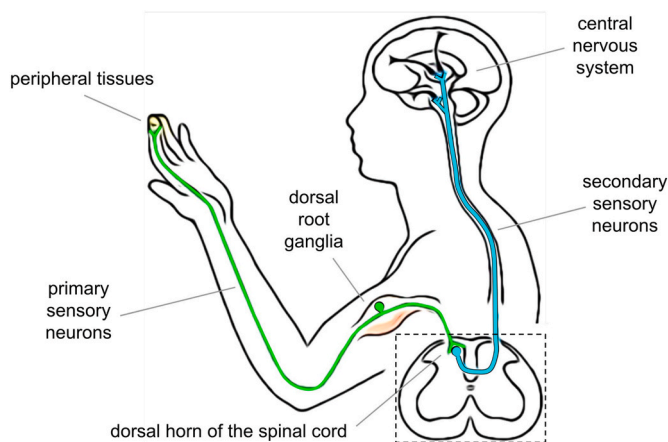


Fig. 1. Pathways for autonomous thermoregulatory responses and thermal perception from peripheral tissues. Adapted from Ref. [36].

2.2. Thermal alliesthesia

Thermal *alliesthesia* is a term originally coined by Cabanac to refer to “the property of a given stimulus to arouse pleasure or displeasure according to the internal state of the subject” [44]. Any thermal stimulus that minimizes the “*thermoregulatory load-error*”, i.e. the discrepancy between the current physiological state and the thermoneutral condition, is perceived as pleasant (“*positive alliesthesia*”), while any stimulus that exacerbates the discrepancy is perceived as unpleasant (“*negative alliesthesia*”). Kuno gives the Japanese open-air *honsen* (a hot spa bath in cold outdoor settings) as an example of a situation designed for producing maximum thermal comfort by deliberately inducing and then easing the thermoregulatory load-error [45].

However, the alliesthesial thermal pleasure is not necessarily predicated on a deviation in body core temperature [46]. Under the transient and non-uniform conditions typically found in the built environment occupants stay within the TNZ of vasomotor regulation. In this zone, the distinction between *temporal* and *spatial alliesthesia*, first articulated by Marks and Gonzalez [47] and empirically confirmed by Parkinson and de Dear [48–52], becomes of greater relevance since the body core temperature remains invariant while the different regional skin temperatures displaced from their “*neutral thresholds*” are responsible for the thermoregulatory load-error. Thus, for the case of spatial thermal alliesthesia, the thermoregulatory load-error emanates from the cutaneous thermoreceptors distributed across the body surface [48–52], while Cabanac’s conventional notion of temporal alliesthesia considers that pleasure is driven by load-errors emanating from the body core [44]. Temporal alliesthesia appears to also emanate from cutaneous thermoreceptors during time-varying thermal conditions that do not affect the body core temperature. For example, Zhang observed that alliesthesia-induced votes of “*very comfortable*” occurred either during transient environmental exposures when a thermal stress is suddenly removed (temporal alliesthesia), or in steady-state but non-uniform environments when the cool or warm feeling from one or more body parts reduces whole-body discomfort (spatial alliesthesia) [20–22].

Alliesthesia is a phenomenon relating specifically to the affective and hedonic component of thermal perception, i.e. thermal comfort, and does not seem to influence thermal sensation which instead represents a more objective assessment of temperature. Building occupants can experience alliesthesia when undergoing a variation of any environmental or personal variable influencing their thermal comfort. The intensity of the alliesthesial effect has been shown to depend on both the magnitude of the thermoregulatory load-error and the spatial or temporal rate of change in the skin temperature [48,53].

2.3. Thermal habituation

All adaptive processes develop over time intervals but they are characterized by different time requirements depending on the physiological mechanisms involved [54]. Largely because the adaptive thermal comfort research, the long-term adaptive processes have been recognized and characterized [11,12]. There has also been a large amount of research on physiological acclimatization, which accounts for any functional change that reduces physiological strain when exposed to persistent thermal stress, especially to hot environments [55,56]. However, our interest here is on adaptive processes developing over a much shorter temporal scale (i.e., minutes or hours) than physiological acclimatization (i.e., days or weeks). These short-term adaptive processes, better known as *habituation* and *sensory adaptation*, are acting at either peripheral or central levels. In particular, habituation is a form of non-associative learning, which occurs within the CNS, whereas sensory adaptation (or sensory fatigue) is directly related to the dynamic activity of primary sensory neurons. They both lead to a diminution of the normal response or sensation magnitude and both have been shown to be reversible [57].

Sensory adaptation has been already characterized as a dynamic

response to rate of change of the stimulus (which we have already introduced in Section 2.1), while little is known on how habituation influences thermal perception, especially during repeated thermal exposures. Most of the thermal comfort experiments dedicated to this phenomenon have dealt with localized thermal stimuli [58–60], while recent insights on thermal habituation are limited to research on thermal pain perception [61–65]. Thermal pain perception is modulated by the same types of molecular temperature sensors and sensory pathways responsible for detecting innocuous heat and cold and, therefore, findings on habituation to repetitive thermal pain stimulations might provide useful insights into how habituation affects the attenuation of thermal perception. For example, habituation to thermal pain is characterized by a decay and saturation process, is more prominent at low and moderate temperatures, and seems to be more pronounced in women [61–65].

3. Dynamic thermal comfort experiments

In this Section, we review thermal comfort experiments investigating transient thermal conditions and performed under controlled conditions in climate chambers. The bibliographic search was conducted through the Scopus® and Web of Science® scientific databases as part of a very recent work reviewing human comfort experiments performed in controlled environmental chambers [66]. As part of this search, 396 journal papers concerning human comfort in experimental facilities were identified, of which 204 directly related to thermal comfort. These studies were further screened to identify those dealing with dynamic conditions, which tallied 35, which were supplemented by another 11 papers overlooked in the original search and found using the “*reference by reference*” method.

A total of 46 papers on dynamic thermal comfort experiments were systematically reviewed according to various criteria, such as:

- the **transient** exposure type (step-change, ramp and drift, cyclical) and the physical characteristics of the dynamic conditions studied,
- the quality of the **physiological** measurements conducted,
- the type of **perception** scales used for the subjective measurements.

The resulting meta-data were tabulated for this review and can be publicly accessed in the Supplementary Materials. The distribution of the reviewed papers in terms of year of publication and type of dynamic condition studied is shown in Fig. 2.

The 46 reviewed experiments have studied a total of 192 different thermal conditions, which correspond to a great variety of thermal environments in terms of temperatures and humidity. With regard to the perception scales used for the subjective measurements, all the reviewed experiments have employed the Thermal Sensation Vote with the great

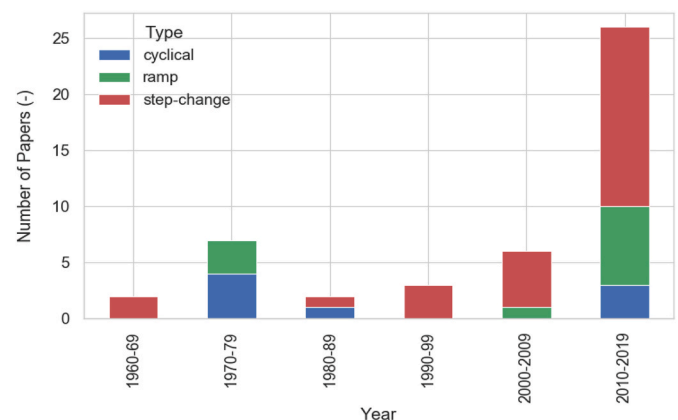


Fig. 2. Distribution of the reviewed dynamic thermal comfort experiments in terms of year of publication and type of dynamic condition studied.

majority of them (67%) using the classical seven-points ASHRAE scale. Concerning the physiological variables, 70% of the reviewed studies have measured skin temperature and 39% of them have also monitored the body core temperature.

The majority of the reviewed studies (27 papers representing 59% of the total) dealt with discrete changes in thermal conditions, e.g. temperature step-change transients (see Section 3.1). The main aim of these experiments is invariably to better understand thermal comfort during transitions between different building thermal zones, or between a building and the outdoors, especially in temporarily occupied spaces. In the last two decades, these studies have been principally performed in Asia. Much fewer studies (11 papers, i.e. 24% of the total) dealt with temperature monotonic ramps and passive drifts (see Section 3.2) but they addressed gradients typically found in buildings: for example, those found in passive solar buildings and/or those induced by the use of a building's thermal mass by "night purging" ventilation strategies or thermally activated building systems such as phase-change materials (PCM). Only a minority of the reviewed studies (8 papers, i.e. 17% of the total) focused on cyclical temperature variations (see Section 3.3) especially relevant to indoor climate-related energy management strategies such as Demand Response (DR) events.

3.1. Step-change

Gagge pioneered dynamic thermal comfort research by conducting an experiment in which subjects moved between rooms at different temperatures and finding that thermal sensation and thermal comfort lead body temperature changes and are thus, "anticipatory" [67]. Over 20 years later, when explaining subjects' thermal sensation overreaction during down-step thermal transients, de Dear called it "overshoot" [68]. Actually, these two terms refer to two slightly different but related phenomena that strongly influence dynamic thermal perception:

- *Anticipation*, i.e. the ability to anticipate the final steady-state sensory response.
- *Overshoot*, i.e. the initial exaggeration of the final steady-state sensory response.

Down-step sensory overshoots are typically found to be approximately twice the size of their up-step counterparts [67–70]. However, rather than comparing sensory overshoots in terms of the rate of change of air temperature, they should be directly related to the time-rate of change of skin temperature since the thermoreceptors' response is directly dependent upon it [48]. In this regard, Zhang obtained a unified linear relationship between the rate of change of mean skin temperature and the initial thermal sensation response to it for both sudden heating and cooling transients [71]. Zhang and Parkinson independently observed that the magnitude of the thermal sensation overshoot also depended on the initial mean skin temperature and, therefore, on the initial load-error [48,72]. Liu and Du found that the thermal sensation vote correlates well with the heat flux from skin surface in both down-step and up-step temperature transients [69,73]. Zhang attributed the sensory overshoot phenomenon to the perceived body thermal stress relief and further noted that the overshoot of sensation and comfort during whole-body step-changes was small compared to that observed during localized (body-part) cooling and heating [20–22]. She also found that some subjects always responded with an overshooting during localized cooling, while others never overshoot but she was unable to identify any consistent individual characteristics that correlated with these "thermal signatures" [20–22].

All these observations relate to both thermal sensation and comfort, but alliesthesia appears to only be relevant to the latter. As an example, when passing from a warm to a neutral thermal environment there is an overshoot of cool thermal sensation but also an overshoot of thermal comfort which - for this particular case of positive alliesthesia - implies an overshoot of comfort/pleasure. A cool/warm thermal sensation can,

therefore, be perceived as comfortable and pleasant when it is framed by positive alliesthesia.

A less well understood phenomenon which has been observed during several experiments on temperature step-changes is "habituation" [20–22,67,72,74–76]. In Figs. 3 and 4 we report the mean skin temperature (upper) and the thermal sensation vote (lower) observed in the works of Ji [75] and Zhang [72], respectively. From Figs. 3 and 4 we can observe that when subjects return to the thermally neutral environment (i.e. 26 °C) after being exposed to either warm or cold condition, their neutral mean skin temperature seems to have been modified and, as a result of this, mean skin temperature appears to stabilize to a higher-than-neutral value after a warm exposure, and to a lower-than-neutral value after a cold exposure. This is especially evident compared to the case of persistent exposure to 26 °C represented by the yellow data series in Fig. 3. Superimposed on this mean skin temperature stabilization to higher and lower values, the thermal sensation associated with 26 °C is no longer neutral but shifted in the opposite direction to the preceding thermal sensation i.e. nudged towards slightly warm when coming from cool conditions, and slightly cool when coming from warm conditions.

All the above considerations are relative to step-changes of temperature, only a minority of studies have investigated step-changes of other thermal comfort variables, for example relative humidity at a given air temperature [71,77–79] and metabolic rate [80–85]. Metabolic step-change studies found poor correlation between thermal sensation and skin temperature, and that thermal sensation depended on the rate of change of body core temperature [80,82–84]. Furthermore, subjects appear to be more sensitive to down-steps of activity than up-steps [82]. This seems to suggest that core thermoreceptors exhibit similar behaviour to their cutaneous counterparts in that they depend on the temperature derivative and are more sensitive to cooling than warming gradients. Moreover, it appears that there is some evidence of

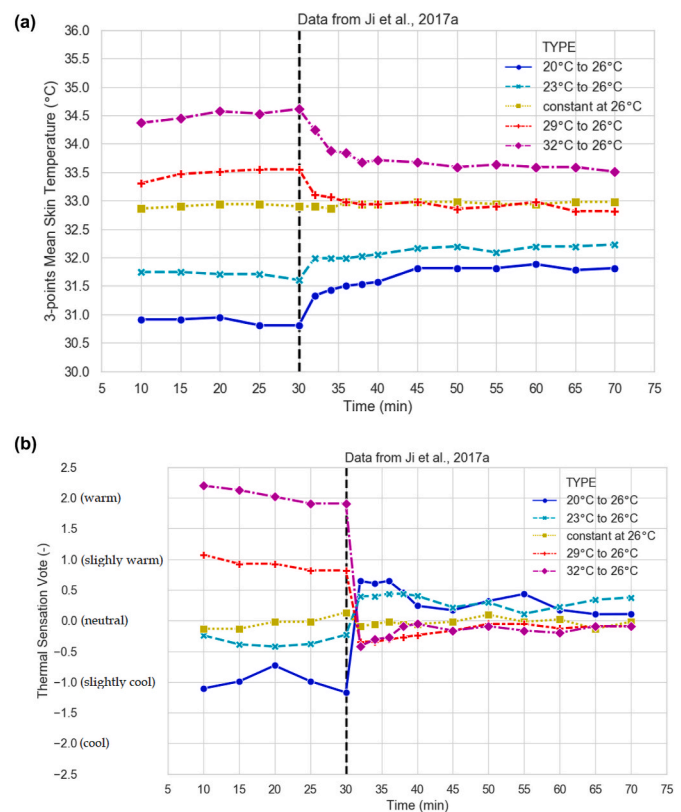


Fig. 3. Mean skin temperature (upper) and Thermal Sensation Vote (lower) observed during temperature step-change transients (Time₃₀). Data are from Ref. [75].

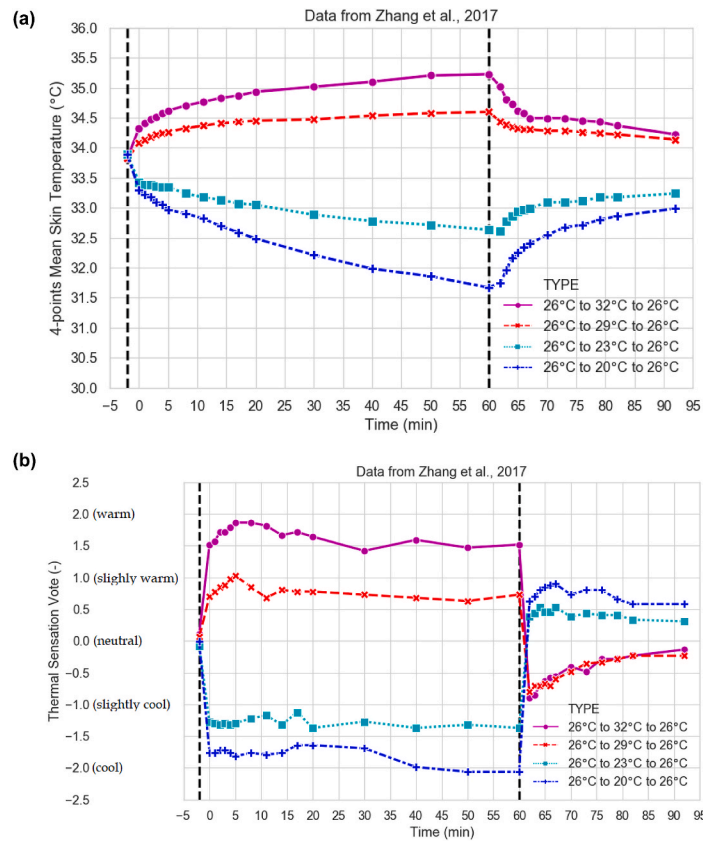


Fig. 4. Mean skin temperature (upper) and Thermal Sensation Vote (lower) observed during temperature step-change transients (Time_{e60}). Data are from Ref. [72].

habituation even in these metabolic transients. For example, in Fig. 5 we see experimental data collected by Tan [84] who exposed 20 subjects to the following variations of metabolic rate: 1 met (30 min) - 2 met (30 min) - 1 met (30 min) - 2.6 met (30 min) - 1 met (30 min). The other comfort variables were kept constant over the course of the experiment and, in particular, the temperature was held steady at 25 °C. The 3 conditions at 1 met were meant to be very close to neutrality (PMV = 0.2) and constant throughout the experiment. However, we observe that after the walking activities at 2 and 2.6 met subjects felt cooler than predicted by PMV. Similarly, to what observed in Figs. 3 and 4, it seems that the warm exposure due to endogenous metabolic thermogenesis led to an exaggeration of the subjective cooling experienced after returning to a sedentary state. However, body core and skin temperatures were not measured in this study so it cannot be confirmed if the observed discrepancy between thermal sensation vote and PMV is due to a form of habituation.

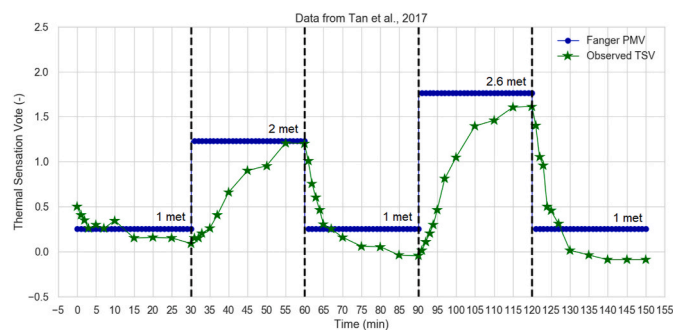


Fig. 5. Thermal Sensation Vote observed during metabolic step-change transients. Data are from Ref. [84].

3.2. Ramp and drift

Studies on ramps (monotonic temperature variations) and passive drifts have mostly looked at low rates of temperature change between 0.5 °C/h and 2.4 °C/h, and have found that sensory responses do not differ appreciably from those registered under steady-state exposures. In particular, rates of temperature change equal or less than 0.5 °C/h appear to be almost indistinguishable from steady-state exposures [86, 87].

Some of these studies have also investigated subjective responses other than thermal sensation such as intensity of sick-building syndrome (SBS) symptoms (e.g. headache or irritated eyes), perception of air quality, and occupant performance, and generally found little or no difference between steady-state and transient conditions when the rate of temperature change is lower than 2.4 °C/h [88–90]. A couple of recent experiments have studied ramps of relative humidity at a given air temperature [91,92].

3.3. Cyclical

Cyclical temperature variations are the most interesting conditions to study because they have the best potential to unfold the dynamic phenomena discussed in Section 2 and can be applied in actual built environmental scenarios such as DR control strategies. During the '70s and '80s few laboratory investigations were conducted into cyclical temperature variations [93–96]. These studies were quite ambitious compared to more recent studies as they often employed a large number of subjects, e.g. up to 800 participants in the experiment of Rohles [96], who were exposed to a great variety of cyclical conditions. However, the analyses of these studies mainly focused on trying to establish a dynamic thermal comfort zone by relating thermal comfort votes directly to environmental variables. In this regard their interpretations were mixed and unable to establish whether dynamic exposures extended or shrank

the steady-state comfort zone. In his review of these studies, Hensen concluded that, for rates below 1.5 °C/h, there is no change in Fanger's steady-state comfort zone [24]. Incongruences and inconsistent findings in interpreting the results of these studies might be related to the fact that their analyses were oblivious to the alliesthesia and habituation effects introduced in Section 2.

More recent research on cyclical temperature conditions narrows down to 3 laboratory experiments [97–99], which are mainly relevant to warm summer conditions. Results indicate that cyclical changes in temperature have a favourable impact on occupants' thermal comfort, even under the high rates of temperature change studied in Zhang's experiment [98]. Indeed, Zhang used the largest sample of participants exposed to the highest rates of temperature change (up to 30 °C/h) and the largest variety of cyclical conditions. Therefore, it is of particular interest [100] and its main results will be briefly recalled here for their particular significance.

In Zhang's experiment 56 students were exposed to six different cyclical temperature variations, with each variation having an overall duration of 2 h (see Figs. 6 and 7). The study was conducted in summer and was specifically addressing an air-conditioning (cooling) case. The experimental sessions were characterized by adapting temperatures (i.e. the temperature to which the skin is adapted for the half hour preceding the temperature cycle) of 22 °C (conditions no. 2, 3 and 4 in Fig. 6) and near-neutrality 24 °C (conditions no. 5, 6 and 7 in Fig. 7). From a qualitative analysis of Figs. 6 and 7, we can recognize the two phenomena of overshoot and habituation when comparing the predicted PMV with the observed mean thermal sensation vote (TSV). In particular, when the temperature moves away from the neutral condition (i.e. when PMV diverges from the zero) the TSV is warmer than the PMV, but when the ambient temperature returns towards the neutral condition (i.e. when PMV approaches the zero) the TSV is colder than the PMV. This is due to the anticipation and overshooting phenomena discussed in Section 3.1 and is particularly evident in those exposures with high rates of air temperature change (i.e. Conditions 4, 6 and 7). To help visualize the process of habituation we have superimposed a shaded band between the initial TSV and the maximum TSV experienced in the first temperature cycle for each condition. In the absence of any thermal history effects we would expect the TSV to keep within this shaded band over the subsequent cycles. However, we observe that, after the first cycle, the TSV stabilizes to a lower value compared to the initial thermal sensation. This is particularly evident in Conditions 3 and 7.

In Fig. 8 we show the observed percentage of dissatisfied subjects (PD) which is interpreted from a binary thermal acceptability scale and is defined as the ratio of thermally unacceptable votes to total votes. This is shown together with Fanger's Predicted Percentage Dissatisfied (PPD)

model for comparison. It is worth noting that Fanger's PPD index is derived using a different definition for the percentage of dissatisfied subjects, namely the percent of people voting above slightly warm or below slightly cool (≥ 2 or ≤ -2) on the seven-point ASHRAE thermal sensation scale. From Fig. 8 we observe that when the temperature moves away from the neutral condition (i.e. when PMV diverges from the zero) the PD is greater than the PPD (negative alliesthesia), but when the ambient temperature returns towards the neutral condition (i.e. when PMV approaches the zero) the PD is lower than the PPD (positive alliesthesia). Furthermore, habituation appears to greatly reduce dissatisfaction levels during the second cycle. This is particularly evident in the Conditions 3, 6 and 7.

4. Existing gaps and agenda for future research

In this Section, we summarize open research questions related to both the phenomenon of alliesthesia and habituation occurring during dynamic thermal exposures (Section 4.1) and set an agenda for future research (Section 4.2).

4.1. Research gaps

In Section 2.1 we have seen that primary and secondary neurons are responsible for encoding, registering and transmitting the thermal information to the brain (Fig. 1). In particular, it has been recently found that the perception of innocuous skin warming depends on cold-activated TRPM8 primary neurons [37]. This neuroscientific evidence encourages us to look at dynamic thermal perception through different lenses than those found in the literature to date. The dynamic sensory response has been hitherto mainly related to the magnitude and direction of the rate of change of skin temperature, with cooling predominant over warming in eliciting thermal sensation overshoots (see Section 3.1). However, if the dynamic behaviour of cutaneous thermoreceptors depends on both the rate of change of the skin temperature and the absolute skin temperature [34,35] and if the detection of the warming rate is related to the inhibition of the firing rate of cold receptors and is, therefore, inherently linked with cold detection [37], then the dynamic response might depend on the sign and magnitude of the load-error (i.e. on the absolute skin temperature) in addition to the sign and magnitude of the rate of change of the skin temperature. For example, the warming-induced thermal sensation overshoot might be stronger under cold than under warm conditions.

There is also the need to quantify how the rate of change of body core temperature affects the dynamic thermal perception. The dependency of sensory detection from the rate of change of body core temperature has

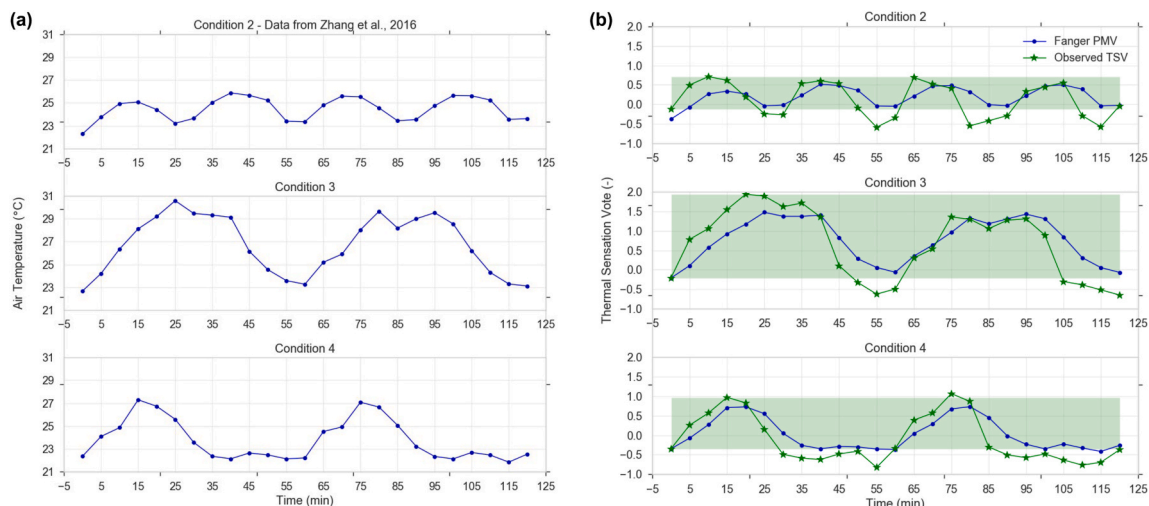


Fig. 6. Air temperature (left) and Thermal Sensation Vote (right) observed during cyclical temperature transients. Data are from Ref. [98].

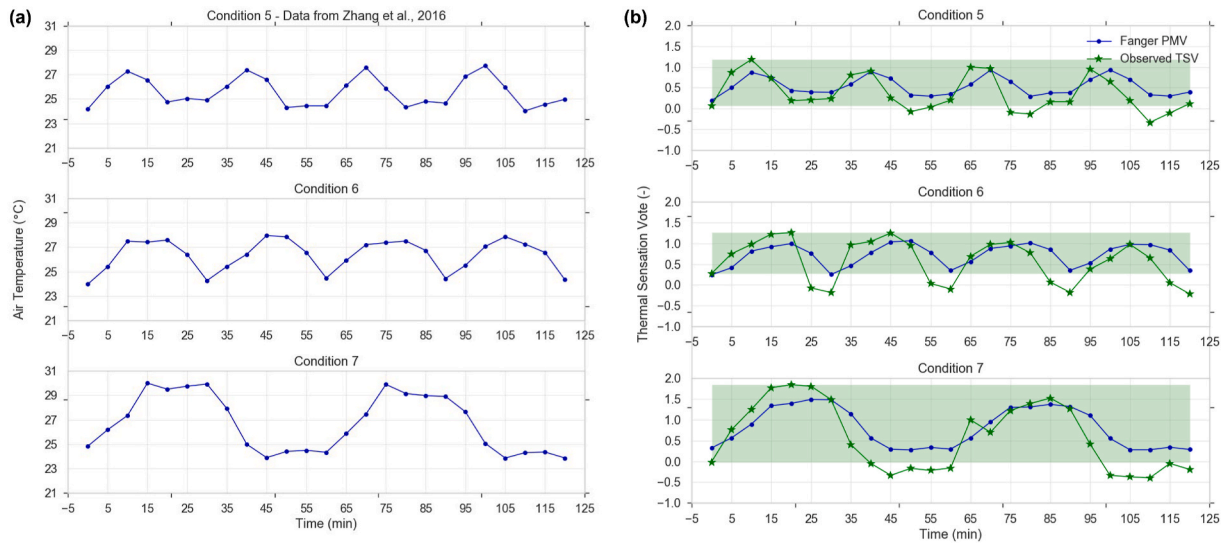


Fig. 7. Air temperature (left) and Thermal Sensation Vote (right) observed during cyclical temperature transients. Data are from Ref. [98].

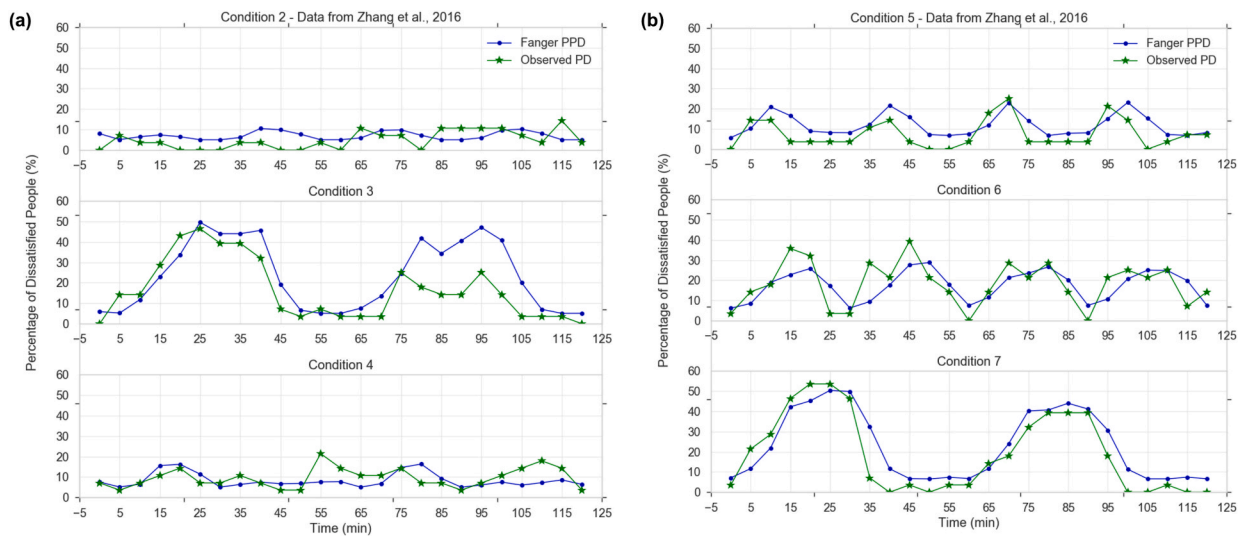


Fig. 8. Percentage of Dissatisfied People observed during cyclical temperature transients. Data are from Ref. [98].

almost been completely overlooked to date, also demonstrated by the fact that the physiologically-based thermal perception models presented in Section 1.2 ignore body core temperature dynamics. As we have seen before, changes in body core temperature are detected by thermoreceptors located throughout the body core, including the viscera, the spinal cord and the brain. While peripheral thermosensation is dominated by the cold sense, central thermosensation, and in particular from *central/core thermoreceptors* located in the hypothalamus, might be dominated by the warm sense. In fact, core overheating is more dangerous than overcooling due to the closer vicinity of human body core temperature to the upper survival limit [38,101]. This suggests that warming transients of the body core temperature might elicit a stronger overshoot than cooling transients, thus reversing the pattern observed for peripheral thermoreception.

Finally, the process of thermal habituation under dynamic repeated thermal exposures is yet to be fully characterized. Studies dealing with localized thermal stimuli have shown that habituation is more evident after exposures to cold conditions and greater in the vicinity of the neutral skin temperature [58–60]. Drawing from the insights of these studies, Zhang modelled the habituated thresholds as a function of the skin temperature by means of a logistic function [20–22]. However,

several aspects of the temporal evolution of habituation during repeated thermal exposures are still unknown. A better understanding and a confirmation of the existence of the phenomena of habituation would require measurements of thermo-effector responses, such as skin blood flow, in order to demonstrate that similar alterations of thermoregulatory control are also occurring. This would also clarify the influence of deeper dermal temperatures relative to skin temperature.

We have summarized the above considerations in 10 Research Gaps deserving further attention. It is yet to be understood:

1. Whether cooling and warming rates of the skin temperature have a different impact on warm and cold thermal sensation overshoots and positive and negative thermal comfort alliesthesial effects;
2. Whether their impact differs depending on the magnitude and sign (i.e. warm vs. cold conditions) of the load-error;
3. Whether their impact (and thus the relationship between overshoots and rate of the skin temperature change) is linear;
4. How cooling and warming rates of the body core temperature contribute to the thermal sensation and positive and negative thermal comfort alliesthesial effects;

5. Whether their impact differs depending on the magnitude and sign (i.e. warm vs. cold conditions) of the load-error;
6. How the duration and the intensity of cold and heat discomfort exposures influence the magnitude of thermal habituation;
7. Whether habituation to cold and heat discomfort exposures differs and whether there is a mutual influence;
8. If an asymptote of maximal habituation is reached after a certain number of repeated stimuli (i.e. if there is a decay and saturation process as with thermal pain);
9. For how long the effect of thermal habituation is sustained after the temperature variation has ended;
10. Whether there is an interaction between thermal alliesthesia and thermal habituation and whether gender differences exist in the two phenomena.

4.2. Research agenda

In the review of Section 3 we have identified 46 dynamic thermal comfort studies conducted in controlled climate chambers and studying a great variety of thermal environments in terms of temperatures and humidity. This implies that the empirical basis for addressing the 10 research gaps outlined in Section 4.1 is already available but, at the moment, is scattered and unusable. Hence, the first research effort of this agenda should be dedicated to put together this scattered set of data and made it available in open access to the research community. In the past, similar research efforts have been successful, for example the ASHRAE Global Thermal Comfort Database I, most often referred to as RP-884 database [102], has been recently expanded into its updated version: the ASHRAE Global Thermal Comfort Database II [103]. This is the largest database of worldwide thermal comfort field studies - containing over 100,000 sets of data - and has already greatly contributed to expand our knowledge of adaptive thermal comfort. However, this database does not contain physiological data and, therefore, it is of little utility for developing physiological-based mathematical models of thermal perception. For this specific purpose, we need a new database made of data coming from experiments in controlled environmental chambers and including physiological measurements. The meta-data resulting from this review and available in the supplementary materials can be seen as a first step towards the creation of such a dataset. Of course, there are many challenges ahead, which are mainly related to the non-uniformity of the collected data. For example, while 70% of the reviewed studies have measured skin temperature, they have used a great variety of numbers and locations of the measurement points. Furthermore, thermal comfort votes have been measured with different scales, which make their homogenization challenging.

Despite the outstanding efforts already invested in physiologically-based mathematical models of thermal perception, particularly Zhang's [20–22], their further development is constrained by the paucity of empirical evidence required to disentangle the mechanisms of dynamic thermal perception. Thus, the second research item of this agenda should be dedicated to conduct new experimental research to enlarge the empirical basis and knowledge required to further develop these models. In this regard, there are two main lines of inquiry: one addressing cyclical temperature variations and the other studying dynamic changes of metabolic rate. In fact, from the review of Section 3 we have seen that cyclical thermal conditions are the least studied conditions so far but have the greatest potential to unfold the phenomena affecting the dynamic thermal perception. While, focusing on changes of metabolic rate will permit us to better understand the contribution of body core temperature variations to thermal perception. Furthermore, a better understanding and a confirmation of the existence of the phenomena of habituation would require measurements of thermo-effector responses, such as skin blood flow, which have been largely neglected in current thermal comfort studies.

The third and final research effort should be devoted to the modelling itself. So far, regression-based models have prevailed over other

modelling formalisms. However, the last few years have seen the emergence of a huge number of data-driven approaches which use physiological signals for predicting thermal comfort [104–107]. These models have the disadvantage of requiring a great amount of data for their training and evaluation but these data are becoming increasingly easy to collect which make them a promising form of modelling, especially for their incorporation into HVAC system controls. The emergence of these data-driven physiological-based models is not in contradiction with the research agenda outlined in this paper as knowledge will be always required to understand what's important and what it should be measured as an input of a data-driven model. Hence, filling the research gaps laid out in Section 4.1 can benefit analytical as well as data-driven models.

5. Conclusions

In this paper we provide a comprehensive review concerning thermal perception under non-steady state exposures. The prevailing approach of this review is to explain thermal perception in terms of physiological signals, in particular skin and body core temperature variations. We believe that this is the best way to understand and model dynamic thermal perception, in contrast to previous works which have mainly looked at environmental variables in an attempt to establish a dynamic thermal comfort zone. Furthermore, in this review we focus on the two phenomena of thermal alliesthesia and thermal habituation, which are known to affect the dynamic thermal perception but have received little or no consideration in previous review works and are yet to be fully characterized. A total of 46 experiments conducted in environmental controlled chambers and dealing with dynamic thermal conditions were systematically reviewed depending on the transient exposure type (step-change, ramp and drift, cyclical) and the physical characteristics of the dynamic conditions studied, the quality of the physiological measurements conducted and the perception scales used for the subjective measurements. The meta-data resulting from this review can be publicly accessed and represents a first step towards the creation of a database of thermal comfort and physiological variables from experiments in controlled environmental chambers. Finally, by reviewing the basic processes of thermal perception and by drawing from recent neuro-physiological evidence, we pinpoint ten major research gaps in the domain of dynamic thermal perception and set a research agenda which consists of three main items: creation of an open-access database of thermal comfort and physiological data, conduction of new experimental research on cyclical temperature variations and dynamic changes of metabolic rate and development of new physiological-based models, in particular analytical ones.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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