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COMPREHENSIVE REVIEW

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Drivers of diversity in human thermal perception – A review for holistic comfort models

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ABSTRACT

Understanding the drivers leading to individual differences in human thermal perception has become increasingly important, amongst other things due to challenges such as climate change and an ageing society. This review summarizes existing knowledge related to physiological, psychological, and context-related drivers of diversity in thermal perception. Furthermore, the current state of knowledge is discussed in terms of its applicability in thermal comfort models, by combining modelling approaches of the thermoneutral zone (TNZ) and adaptive thermal heat balance model (ATHB). In conclusion, the results of this review show the clear contribution of some physiological and psychological factors, such as body composition, metabolic rate, adaptation to certain thermal environments and perceived control, to differences in thermal perception. However, the role of other potential diversity-causing parameters, such as age and sex, remain uncertain. Further research is suggested, especially regarding the interaction of different diversity-driving factors with each other, both physiological and psychological, to help establishing a holistic picture.

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Introduction

More than 100 years of research on human thermal perception by a variety of disciplines has led to broad knowledge on general and specific aspects of this topic. Still, the interest in this field of research has been growing again over the last years due to the increasing awareness of individual differences, new approaches in modelling thermal perception for predictive purposes, and global and local challenges with respect to thermal perception, as outlined in the following.

Individual differences

Nicol et al. [1] comment their Figure 10.10 (Figure 1) showing obtained comfort votes against indoor operative temperature: "One of the most instructive things about this for those who are unfamiliar with field survey data will be how scattered the data are." The data presented uncovers the diversity of thermal perception: on the one hand, people are feeling comfortable (4 on y-axis) between 20°C and 28°C. On the other hand, in the range between 22°C and 28°C votes between 'much too warm' (7 on y-axis) and 'much too cool' (1 on y-axis) can be found for any given temperature.

Not surprisingly, the regression of comfort votes against operative temperature explains only 16% of the observed variance in the data. We can expect numerous factors influencing individual thermal perception, which were grouped by Shipworth et al. [2] into physiological, contextual, and psychological properties and states of an individual within a given context, which is partly reflected also in the definition of behavioral, physiological, and psychological adaptive mechanisms by de Dear et al. [3]. Understanding the influencing factors explaining

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Supplemental data can be accessed here

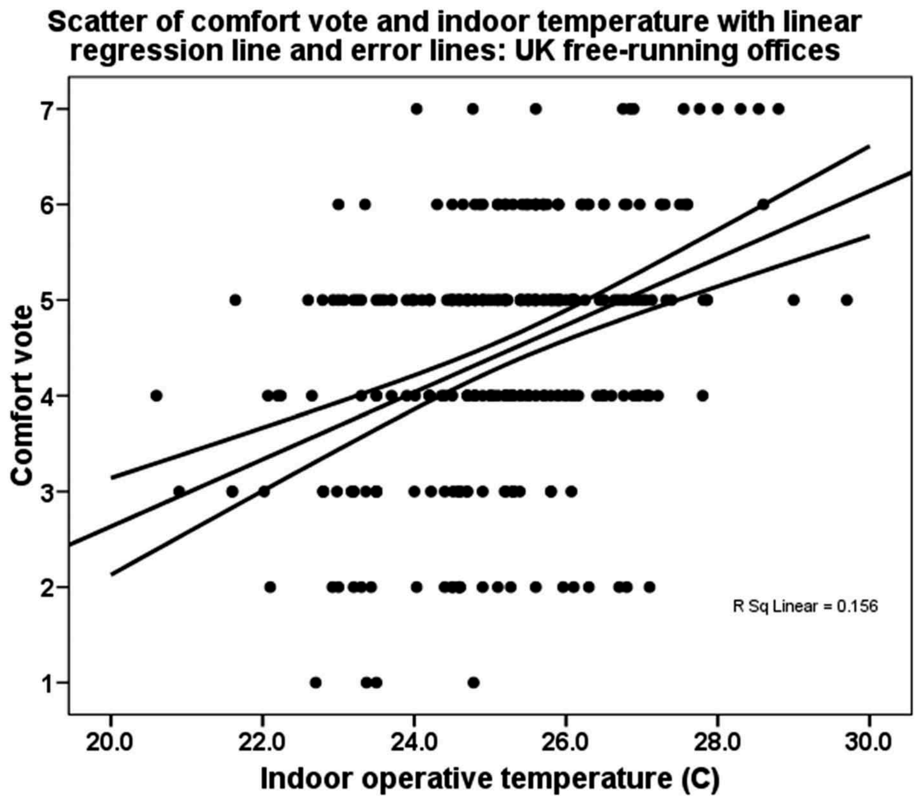

Figure 1. Figure 10.10 from Nicol et al [1,p.138] showing the comfort votes measured against operative temperature together with the regression line for comfort votes on operative temperature. Descriptors for the thermal comfort votes are 1 "much too cool", 2 "too cool", 3 "comfortably cool", 4 "comfortable", 5 "comfortably warm", 6 "too warm", and 7 "much too warm".

the remaining 84% of residual diversity in thermal perception (or at least a large share of it), is important for scientific and practical reasons [2]. From the scientific viewpoint, model construction is a key element supporting the process of knowledge generation. However, as outlined in the next section of this introduction, existing thermal comfort models do not (fully) capture the diversity observed.

Practical reasons mentioned by Shipworth et al. [2] include the arguments that population-based delivery of thermal conditions will leave those occupants in discomfort, whose comfort perception deviates from the population mean and that there is a shift from the need to provide comfort under constraints of energy towards constraints of power. Such arguments need to be emphasized in light of the challenges outlined in the third section of this introduction, which can be expected not to affect all humans equally, but to be more serious for some and less for other individuals.

Modelling approaches

One possible approach, aimed at the quantification of how exactly the same thermal environment influences one individual differently than another, would be to create a mathematical model that incorporates all physical, but also physiological, psychological, and contextual factors, which play a role in thermal perception. Such a model could then be of great use for developers and designers of the next generation buildings that aim to deliver both healthy environments and comfort at near zero energy cost.

Based on recent reviews of thermal comfort models [4–7], the existing modelling approaches can be classified as follows:

- Classic heat balance models (Fangers' predicted mean vote (PMV) [8], PMV adjusted for elevated air speeds [9])
- Adjusted heat balance models (e.g. adaptive PMV (aPMV) [10], extended PMV (ePMV)

[11], newPMV (nPMV) [12], adaptive thermal heat balance (ATHB) model [13,14]), thermoneutral zone (TNZ) and distance to TNZ (dTNZ) [15,16])
- Adaptive comfort models based on regression analysis (e.g. [3,17–19])
- Thermophysiological models (e.g. Gagge's 2-node model [20], the Fiala model [21,22], the UC Berkeley model [23,24], Tanabe's model [25], or ThermoSEM [26]).

The general heat balance model and adaptive models have been successfully applied to explain thermal perception on a population level for steady state conditions. Thermophysiological models have expanded them for dynamic situations that simulate the autonomic mechanisms the body uses to achieve heat balance (skin blood flow regulation, sweating, shivering, etc.).

Despite their variety and in parts complexity, neither of these approaches is able to capture the observed individual differences. That is, while the existing thermophysiological models offer the potential to look at differences due to physiological characteristics (either metabolic heat production, body composition or thermoregulatory function) [27,28]; they do not incorporate physiological or psychological *adaptive* mechanisms.

In contrast, the adjusted heat balance models try to capture effects of thermal adaptation. However, the majority is based on the PMV approach, which – due to its partly empirical nature – does not offer a straightforward solution to include individual differences in physiological characteristics. In addition, findings from social sciences, engineering, and health studies related to these aspects are not integrated.

Not surprisingly, recent works evaluating the predictive performance of several of these models showed that only between 30% and 50% of individual thermal sensation votes were predicted correctly [13].

Global and local challenges related to thermal perception

Concurrent with current models not capturing individual differences sufficiently, human life in residential and office buildings faces multiple challenges demanding a further understanding of individual thermal perception.

Climate change predicts increased average and maximum temperatures in summer and a higher frequency and severity of heat waves [29,30], but also higher precipitation rates, rising sea levels due to melting snow and ice, and warmer oceans. By the end of the 21st century, countries in Central Europe are expected to experience as many hot days as are currently encountered in Southern Europe.

On the one hand, these climatic changes affect the energy use within buildings for providing comfortable indoor conditions, i.e. for heating, cooling, lighting, and ventilation, which accounts for 40% of the energy used within the European Union [31]. Predictions forecast that climate change will increase the need for cooling in summer and decrease the heating demand in winter, with total energy use predicted to rise if no countermeasures are implemented [32]. At the same time, the majority of buildings to be inhabited in 2050 within Europe already exists today. Despite many countries setting renovation rate targets, the actual renovation rate is low. For example, the German government introduced several programs to reach a 3% target, but the achieved renovation rate remains around 1% [33]. Many reports show that predicted savings of renovation measures were not met in reality, because the occupants' expectations towards thermal indoor conditions increased alongside the renovation and led to a higher heating demand in winter [34,35]. The first challenge here is to understand and model individuals' thermal expectations, for the provision of thermally comfortable conditions at minimum energy use despite a changing global and local climatic context.

On the other hand, climate change can be set in relation to other challenges that are often conjointly mentioned with thermal perception: health and productivity. It is broadly established that heat waves and cold spells are associated with thermal discomfort, decreased physical and cognitive performance [36], and increased mortality [37]. While this does not make thermal comfort synonymous to health or productivity per se [38], the constructs are aligned in the way that thermally comfortable conditions are associated with minimal thermoregulatory effort for the body. However, as mentioned in the discussion section of this paper, it may be questionable whether thermally comfortable conditions are always the best conditions one should aim for. Nonetheless, for both perspectives, it is important to develop a better understanding of the drivers of our inter- and intraindividual diversity in thermal perception.

The effect of climate change on human thermal perception, health, and productivity needs further attention due to predicted demographic changes. Firstly, the population in many European countries is ageing; predictions for the EU-28 indicate that the share of the elderly in the total population will increase from 19.2% at the start of 2016 to 29.1% by 2080, corresponding to more than 50 million people [39]. Secondly, in the EU-28, the proportion of adults (aged 18 years and over) who were considered to be overweight is steadily rising and was estimated in 2014 to be approximately 51.6%, whereof 15.9% were obese (BMI >30 kg/m^2) [40]. Given the expected changes in population demographics, there is an increased importance in understanding and modelling thermal perception of these growing subpopulations in comparison to each other and to other subpopulations.

Objectives, scope and definitions

Objectives

Summarizing the three key points from the introduction: (1) it is now understood and accepted that people's thermal perception is diverse (either due to physiological differences or through their lifestyle/behavior). However (2), up until now, existing models predicting thermal perception do not capture such adaptive processes and individual or subpopulation differences holistically. Together with (3), the global and local challenges of climate change, ageing and an increased obesity prevalence, there is an urgent need to understand these individual differences, adaptive processes and potentials better, so that related findings can be implemented in predictive models.

Therefore, this manuscript (1) reviews the existing knowledge related to drivers of diversity in thermal perception and (2) discusses existing gaps for holistic mathematical models of thermal perception by exemplifying possible implementations of drivers of diversity into one existing model.

The research questions are as follows:

- What are the main drivers of diversity in human thermal perception?
- What knowledge is available (and what is missing) in order to implement these drivers into mathematical models for the prediction of human thermal perception?

Scope and definitions

Thermal comfort

Thermal comfort is defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [41].

In the literature on human thermal perception, many terms are used to describe one or another aspect: thermal sensation, thermal preference, thermal dissatisfaction, thermal comfort, neutral temperature, etc. The authors acknowledge that thermal sensation and thermal comfort are not the same, e.g. a warm sensation can be perceived as either comfortable or not comfortable depending on a person's context or preferences. At the same time, the term thermal comfort is used in different ways: (1) when referring to the answers obtained on a question asking specifically for a judgment, between comfortable and not comfortable, (2) when referring to other aspects of people's thermal perception – often the middle three categories of the sensation scale (slightly cool, neutral, slightly warm) –, and (3) when mentioning the general concept of thermal comfort. In this review, we will use thermal comfort solely in case subjects were asked specifically about it or when referring to the general concept of thermally comfortable condition. Otherwise, the term thermal perception or the construct observed, e.g. sensation, will be used.

The scope of the section discussing the integration of drivers of diversity into models is on the effect of drivers of diversity on people's satisfaction with the thermal environment. Therefore, the term predicted percentage of satisfied (PPS) is used, which can be regarded as the inverse function of the predicted percentage of dissatisfied (PPD) introduced by Fanger [8].

Drivers of diversity

Thermally comfortable conditions are defined in international and European standards [41–43] through a set of equations. These equations have as independent variables solely physical variables: either four parameters of the indoor environment (room air temperature, radiant temperature of surfaces, air velocity, and relative humidity) together with the activity and clothing insulation level (CLO) of the individual [8] or, for the adaptive comfort model(s), the running mean of the daily mean outdoor temperature [44,45]. While these seven variables are able to explain part of the variance seen e.g. in Figure 1 by Nicol et al. [1], which is based on operative temperature only, there remains a high variance even when all six variables are considered. Given the definition of thermal comfort by ASHRAE cited above [41], psychological factors can be expected to play another role. As pointed out by de Dear [46], environmental psychology is a discipline that should have made a larger contribution to research on thermal perception.

With respect to adaptability, several sources provide different comfort ranges. Around the comfort temperature determined at a particular day, for 80% occupancy acceptability, a comfort zone width of ±3.5 K [41], or ±3.0 K is allowed [43]. The extended comfort ranges (seasonal variation) of adaptive comfort models rely on the assumption that occupants can freely adjust, and acclimatize to several environmental parameters such as air speed, humidity levels and clothing.

At the same time, research has shown that

(1) people accept much broader thermal conditions than anticipated by above standards [1,3,14,47], and
(2) their perception of thermal conditions is much more dynamic [48–51].

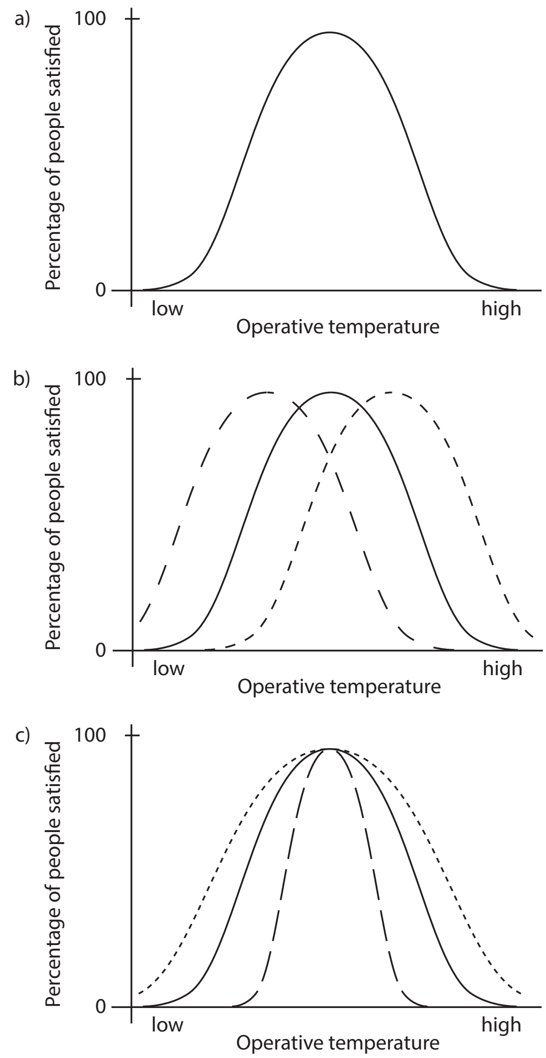

Figure 2. Influences on the relationship between physical conditions and the percentage of people satisfied. Inter- or intrapersonal differences in physiological, psychological, and/or context related drivers can lead to (b) a shift of the PPS-curve to the left or right and/or (c) a wider/narrower curve.

Variables explaining such variance will be called drivers of diversity and grouped according to Shipworth et al. [2] into physiological, psychological,[1] as well as context related variables. The individual drivers include variables, which can lead to within-subject diversity (e.g. different adaptation levels between winter and summer, or emotions) and/or between-subject diversity (e.g. different age, sex, ethnicity, or adaptation level due to spending different amounts of time in air-conditioned (AC) or naturally ventilated (NV) buildings and outdoors).

Figure 2 summarizes the potential effect of distinct drivers of diversity on the relationship between physical conditions and the percentage of people being satisfied (PPS).

Methods

The following subsections describe the methods used for reviewing the existing knowledge of drivers of diversity and the modelling approach applied for the discussion of such findings.

Review methods

The review for this paper was structured in two stages. In the first stage, existing review papers were analyzed with respect to physiological, psychological, and context-related drivers of diversity.

Review of reviews

Search method. Within the bibliographic databases Science Direct and Scopus, the initial search used the search term "'review' AND 'thermal comfort'". Bibliographical information and the abstracts of all identified papers were imported into the review software Parsifal [52]. Duplicated records were removed.

Criteria. The titles and abstracts of the remaining records were screened based on the following inclusion and exclusion criteria. The single inclusion criterion was that the type of record was a review paper. Exclusion criteria were

- not dealing with thermal perception
- no diversity aspect mentioned in abstract
- reviews of outdoor thermal comfort studies
- reviews of simulation/mannequin studies

Data extraction. In this first screening, the type of diversity factor reviewed, and the number of studies referred to according to each diversity factor were extracted.

The initial search in Science Direct and Scopus, using the broad search terms "thermal comfort" AND review, revealed several comprehensive review papers, which have earlier sought to aggregate the influence of individual physiological factors on thermal perception from original papers. These earlier review papers focused mainly on one or a few demographic or physiological variables each; however, in their entirety they were judged sufficient as revealing the state of knowledge regarding physiological drivers. Therefore, for potential physiological drivers of diversity, a review of existing review papers has been conducted as part of the present review, to avoid repeating work that has already been done but to provide a broad overview of diversity factors identified by those already available, earlier publications.

For both psychological and contextual factors, existing review literature identified by the first stage of search was scarce and not sufficiently covering potential drivers of diversity, which is why in a second stage, original literature was reviewed for both factors.

Review of original papers

In the second stage, additional rapid evidence assessments (REA) were conducted based on original papers for individual factors. Again, the utilized databases were Science Direct and Scopus. The search terms described in each individual section were searched for in title, keywords and abstract of papers. The searches were carried out in June and July 2018. Additionally, papers known to the authors were added. Bibliographical information and the abstract of all identified papers were imported into the review software Parsifal [52]. Initial screening was done based on the abstract. For papers remaining after this step, the full text was then assessed and if relevant, information extracted. The same exclusion criteria as for the review of reviews were used.

The following strategies were applied for the following concepts:

Specific review strategies for psychological drivers

As there were no relevant review articles identified for psychological drivers in stage one, a rapid evidence assessment on original empirical works (as opposed to review papers) was conducted. Table 1 shows the keywords and their combinations used in the search for this part. Keywords were chosen to be relatively generic to increase the chances of capturing relevant research, e.g. *psychology* and

Table 1. Search keywords to identify psychological drivers.

Comfort keywords		Location keywords		Psychological keywords
Thermal comfort		Office/s		Personality
OR		OR		OR
Thermal sensation		Building/s		Emotion
OR		OR		OR
Thermal preference	AND	Built environment	AND	Cognition
OR		OR		OR
Neutral temperature		Chamber		Perceived control
				OR
				Personal control
				OR
				Psychology
				OR
				Psychological

cognition. In addition, more specific keywords were chosen where we knew that research existed, e.g. *personal control* and *personality*. An additional inclusion criterion was that the paper needed to address a psychological diversity factor.

Specific review strategies for context-related drivers

Several relevant review papers for context-related drivers were identified in stage one, but additional search terms were used to focus on specific aspects of the built environment that impact thermal perception. The keywords used were "review" and "comfort" and one out of "thermal mass", "ventilation strategy", "radiant", "asymmetry", or "air speed". These keywords were chosen since these aspects are considered to be the most relevant context-related drivers according to the review papers found in stage one. Although the search terms include the criterion "review", many of the results involved original research papers, which, if found relevant, have been included. Moreover, relevant original papers that were cited in these papers have been consulted.

Modelling

The discussion on ways forward towards a holistic mathematical model uses a combination of the TNZ model by Kingma et al. [15] and the ATHB framework by Schweiker and Wagner [14].

The TNZ model is a steady state heat balance model, which explicitly combines internal (within body), and external (from body to environment) heat balances. The intended use of the TNZ model is to find the combinations of body core temperature, skin temperature and operative temperature that 1) support both internal and external heat balance, and 2) are physiologically feasible. The internal heat balance is dependent on heat production, body tissue insulation, body core, and skin temperatures. The external heat balance is dependent on heat production, clothing insulation, air speed, skin wettedness, relative humidity, skin and operative temperatures. Physiologically feasible solutions are defined where body core temperature is within a specific range (e.g. 36.5°C to 37.5°C), and body tissue insulation is constrained to what is within thermoregulatory bounds (e.g. highest body tissue insulation for maximal vasoconstriction and lowest body tissue insulation for maximal vasodilation). The TNZ model can be used to calculate the traditional physiological thermoneutral zone; that is, "the range of ambient temperature at which temperature regulation is achieved only by control of sensible (dry) heat loss, i.e. without regulatory changes in metabolic heat production or evaporative heat loss". Previous research suggests that the distance ($dTNZ_{op}$) of the actual (measured) operative temperature (T_{op}) to the operative temperature in the center of the TNZ ($T_{op\ centroid}$) (see Figure 3) is related to the thermal sensation vote [16,53].

With the introduction of the TNZ model it was also shown that the "thermal comfort zone" lies within the physiological thermoneutral zone, and that they share the same center [15]. Such results imply that the TNZ model can be applied also in the context of thermal satisfaction or thermal comfort. The validity of such rationale can be assessed preliminary by looking at the probability density function (pdf) of all combinations of operative temperature and skin temperature leading to a core temperature within the thermoneutral zone (pdf_{TNZ}), i.e. between e.g. 36.5°C and 37.5°C. For the same environmental conditions, Figure 3 shows a close relationship between pdf_{TNZ} and the PPS curve – the latter based on Fangers' PMV. Therefore, the applicability of the pdf_{TNZ} to look at the effect of a specific driver of diversity on thermal satisfaction appears a valid approach for the discussion. However, the PMV-PPD relationship by Fanger is solely based on thermal sensation votes together with the assumption that dissatisfaction is expressed

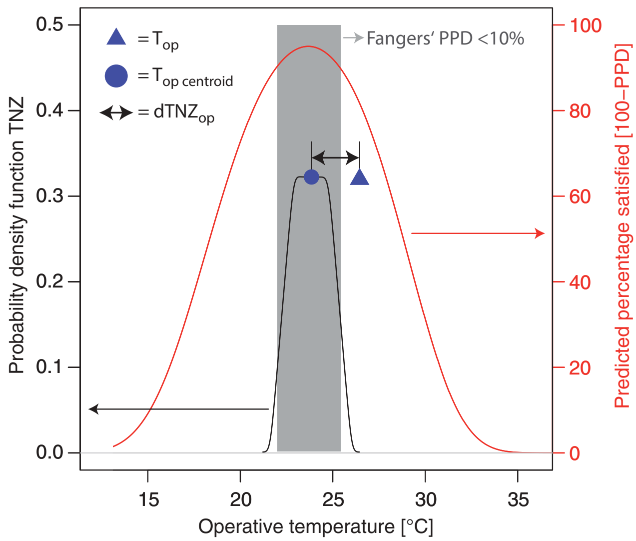

Figure 3. Relationship between probability density function (pdf) of solutions for TNZ, Top centroid and dTNZop, pdf of TNZ and PPS curve. The pdf (black line) is for a standard female person. The red line shows the predicted percentage of satisfied (PPS), which is the inverse of the predicted percentage of dissatisfied (PPD), as defined by Fanger [8]. The PPS line is based on the same environmental conditions as the pdf-lines. The gray area shows the range of Top, which is related to a PPD by Fanger below 10%.

by thermal sensation votes outside the three middle categories [8]. Therefore, the close relationship between pdf_{TNZ} and PPS cannot be regarded as a sufficient argument for the applicability of TNZ model for questions regarding thermal satisfaction or thermal comfort. Further comparisons need to be done with obtained comfort votes as described below.

The ATHB approach [13,14] offers a framework to include individual processes of thermal adaptation (behavioral, physiological, psychological) into the heat balance by Fanger [14] and the SET model by Gagge [13,14]. In short, Schweiker and Wagner [14] modeled

a. behavioral adaptation by adjusting the clothing insulation level based on the running mean outdoor temperature (T_{rm}) according to

$$CLO_{adapt} = 1.252594 \; - 0.03 * T_{rm} \quad with\ 0.46 < CLO_{adapt} < 1 \tag{1}$$

b. physiological adaptation by adjusting the metabolic rate related to the given activity (MET_0) based on T_{rm} through

$$MET_{adapt} = MET_0 - 0.017756 * (T_{rm} - \; 18) \quad with\ MET_{adapt} \geq MET_0 \tag{2}$$

c. psychological adaptation by adjusting the metabolic rate either based on a fixed value related to a specific and fixed psychological effect such as the number of persons in a room or a variable value depending e.g. on indoor operative temperature.

The TNZ model offers similar opportunities to include individual processes for adaptive mechanisms as the PMV and SET model. In contrast to PMV and SET, the TNZ model also offers the potential to vary additional input parameters such as age, sex, and body tissue insulation, relevant for the discussion of findings based on the literature review. At the same time, the TNZ model is still a rather simple model compared to more complex thermoregulative models, so that the implementation of adaptive mechanisms could be done straightforward. Therefore, these two approaches offer the potential to look at individual differences and adaptive processes in thermal sensation and thermal satisfaction. The validity to combine the ATHB approach with the TNZ model will be discussed alongside with the results from the review and existing gaps in the literature.

Review results

A summary of the number of studies processed in each step outlined below is shown in Table 2.

Physiological drivers of diversity in thermal perception

The physiological basis of thermal reception lies for a great part in the integration of body temperature via temperature sensitive neurons [54]. It has been proposed that the relative contribution of core and skin temperatures to thermal comfort is approximately 50%:50% [55]. This makes physiological factors that affect body temperature distribution such as body composition and acclimatization state important to consider.

Nonetheless, thermal perception is not a product of neural thermal reception alone. It has been

Table 2. Number of records processed in each step of the reviews.

Step	Review of reviews (covering physiological drivers)	Review of psychological drivers	Review of context related drivers
Records identified with initial search	408	332	408
Records remaining after de-duplication	290	207	290
Records included based on title/abstract	19	59	6
Records included after full screening	9	12	4

well-established that an individual's thermal perception and perception of comfort is, amongst other things, influenced by that specific individual's physical condition. This physical condition of an individual's body is determined by demographic factors, which are a given, such as sex and age, and a number of physiological variables such as body composition, adaptation state, and level of fitness, which might change over time or according to the situation.

A great body of original research has sought to better understand the interplay and impact of these factors on thermal perception, by evaluating individual subjective responses in a wide range of ambient conditions, from neutral to the extremes, and in all possible set-ups such as artificial laboratory environments, but also in homes, commercial buildings, offices, schools, universities etc., in many different parts of the world.

In the following, we will present an overall summary of the available literature reviews regarding demographic and physiological parameters and the role of these parameters as "drivers of diversity in thermal perception".

Nine records were retained for the review. The potentially diversity-driving factors that have been identified amongst these review papers include age, sex, body composition and fitness, metabolic rate, and physiological adaptation due to temperature acclimation and habituation of different climatic zones, seasonal adaptation, and circadian/ diurnal rhythm.

Age

From a physiological perspective, thermoregulatory capabilities change substantially from childhood to old age. These physiological changes include, for example, a lower body temperature in both older males and females as well as structural changes of the skin and metabolic alterations. They are a consequence of changes of thermal effectors such as the abilities to sweat, shiver and control skin blood flow, and also changes in sensory function, which is also likely to cause discrepancies in thermal perception [56]. With increasing age, thermoregulatory capacities of the human body have been shown to decline, especially if also the level of fitness recedes. For a broad overview of age-dependent changes in thermoregulation, the reader is referred to a recent review by Blatteis [57].

Five review papers have been identified that discuss the influence of age on preferred temperature or synonymous concepts such as neutral temperature or thermal comfort (Table 3) [58–62]. Overall, the results were ambiguous. Already in his review from 1973 [58], Fanger appreciated the fact that aging of the body brings along changes, amongst other things a slower metabolism and thus less heat production. In theory, this might lead to a higher preferred temperature of the elderly, however, from his analysis he concluded that age did not have an influence on preferred ambient temperature. Fanger explains this with a lower evaporative heat loss in the elderly, which would compensate for the lower metabolism. In contrast, a later review by van Hoof [61] established that differences in preferred ambient temperatures were evident in several studies, stating that older people preferred higher temperatures, which the author ascribed to lower activity levels and lower basal metabolic rate. Importantly, Rupp, Vasquez and Lamberts [60] report that field studies amongst young children showed they preferred lower temperatures than those predicted by the PMV. In part, the lower preferred temperatures could be explained by increasing the metabolic rate input for children by 20%. Moreover, one of the factors mentioned is that children seem to have a greater sensitivity to changes in their metabolism. This can be explained with a smaller absolute mass in children, as equal changes in metabolic rate (W/m^2) should therefore result in a larger change in body temperature in children compared to adults, and therefore may explain a greater sensitivity to changes in metabolic rate.

Table 3. Summary of literature review related to age as physiological driver of diversity.

Reference, year	No. of papers reviewed by reference (for the specific diversity factor)	Methodological quality of the literature review	General conclusion(s)	Effect of diversity factor on thermal comfort established by review
Fanger, 1973 [58]	7	Non-systematic review, field & laboratory studies (verify)	No influence of age on preferred ambient temperature	–
Van Hoof, 2008 [61]	3	Non-systematic review, field & laboratory	Older adults do not principally perceive comfort differently from younger groups but might have lower activity level and basal metabolism resulting in a preference of higher ambient temperature.	±
Mishra and Ramgopal, 2013 [59]	5	Non-systematic review, only field studies	Three studies indicate elderly feeling cooler or preferring a higher ambient temperature; two papers state differences in neutral temperature but results of those not conclusive.	±
Rupp, Vasquez and Lamberts, 2015 [60]	8	Systematic review; 2 laboratory studies, 3 field studies	Laboratory studies: One study states no effect of age; another study does report that older people had more distal vasoconstriction and preferred a higher temperature than young adults. Field studies: Young children compared with adults have greater sensitivity to changes in their metabolism and prefer lower temperatures than those predicted by PMV. Two field studies in naturally-ventilated buildings found no significant relationship between age and thermal comfort.	±
Wang et al., 2018 [62]	14	Systematic review, 4 laboratory studies, 10 field studies	Laboratory studies: Three out of four studies do not find significant age-related difference in preferred room temperature; one study claims weak difference but does not report significance values. Field studies: Two studies report significant age-related differences in comfort temperatures, both stating that the elderly preferred higher temperatures than the younger counterparts. One other study reported the opposite, a higher comfort temperature for younger subjects (below 25): 0.7°C higher than senior subjects (older than 25). Yet another study reports that the PMV model overestimates the mean neutral temperature for elderly people by 5°C in winter, but underestimates by 0.3°C in summer. Two studies report weak age-related differences, but no significance reported. Four studies report no significant relationship between thermal comfort and age.	±

In general, the evidence for age-related differences of preferred temperature/comfort temperature is unclear and it is therefore difficult to draw definite conclusions from the available data. Only few of the studies mentioned in the respective reviews presented in Table 3 describe a distinct, significant difference of neutral/preferred/comfort temperature amongst different age groups. If a difference is reported, in all but one case, higher preferred temperatures in elderly were evident. In contrast, young children and infants preferred lower temperatures, when compared with college-aged/middle-aged populations.

Sex

Seven reviews have been identified that evaluate the body of original evidence regarding sex-based differences of thermal perception (Table 4). Physiological grounds for thermoregulatory differences between men and women are manifold. For example, women have a higher surface-to-volume ratio (which allows for greater heat loss via the skin), different body composition (higher fat mass and less muscle mass) and lower metabolic rate (less [metabolically-active] fat-free mass in women and thus up to 20% less heat production [63–65]). This lower heat production in women is partly compensated for by their lower body surface area, but not completely [66].[2]

In summary, most original studies identified by the review papers presented in Table 4 report women to be more sensitive to temperature fluctuations, women to be more often dissatisfied than men, women to have smaller comfort zones and to be more often uncomfortably hot or cold than men [59–61,67]. Also, different clothing patterns of women and men are regularly reported in field studies, with women usually exhibiting lower CLO values than men [59,67]. The latter might at least for some part explain the differences in thermal sensation and thermal preference between women and men. For neutral temperature, however, a systematic review by Wang et al. [62], presenting results from eleven laboratory and 25 field studies, found no significant differences between men and women in nine out of eleven laboratory studies and in 18 out of 25 field studies.

Body composition and fitness

Body composition is an important parameter in thermoregulation of the human body. For example, a thick subcutaneous fat layer increases insulation and attenuates heat exchange via the skin, which helps maintaining body core temperature in a cold environment [15,68]. Heat loss, on the other hand, might theoretically be impaired in higher temperatures when the subcutaneous fat layer is thicker. Several earlier physiological researches report higher body temperatures in obese individuals when compared with lean counterparts upon heat exposure and exercise [69–71]. However, other studies have shown no effect of body fat percentage on heat loss and/or body temperature, which the authors have attributed to high skin blood flow in heat and exercise [72–74]. The latter might overrule the conductive resistance of peripheral adipose tissue.

The amount of fat-free mass, which for a major part consist of muscle tissue, inversely relates to body tissue insulation in resting conditions. That is, having more of well perfused muscle lowers insulation by the body. For resting conditions, muscle mass can explain up to 90% of body tissue insulation, whereas in more active conditions (when muscle gets even more perfused), the subcutaneous fat layer is the only layer of insulation that we have left [68]. Next to insulation, lean mass strongly determines heat production (metabolic rate) of the body: the greater the muscle mass, the more heat is produced by the body, even in a resting state [75,76]. Therefore, it can be assumed that thermal perception and preferred temperature are affected by body composition.

One review was identified, which assesses the effect of BMI on thermal perception [62] (Table 5). Out of four laboratory studies in normal-weight and overweight children, three show significant differences in thermal sensation between the two groups [70,74,77]. Overweight children perceived the thermal environment as being hotter than the non-overweight group, with corresponding higher body temperatures in the overweight children. Similar results were obtained by office studies in adults, showing that comfort temperature decreased with increasing BMI [78–80].

Table 4. Summary of literature review related to sex as physiological driver of diversity.

Reference, year	No. of papers reviewed by reference (for the specific diversity factor)	Methodological quality of the literature review	General conclusion(s)	Effect of diversity factor on thermal comfort established by review
Fanger, 1973 [58]	3	Non-systematic	No difference between men and women; Fanger claims that the slightly lower skin temperature and evaporative heat loss are balanced by lower metabolism in women.	–
Van Hoof, 2008 [61]	4	Non-systematic	Women are more sensitive to temperature fluctuations. Three studies report either higher comfort temperatures of females or, respectively, women feeling cooler when compared with men in the same ambient conditions, especially in cool conditions. Another study reported females were less satisfied with room temperature than men, feeling both uncomfortably hot and cold more often than males, and preferred higher room temperatures.	+
Karjalainen, 2012 [67]	49	Systematic, 20 laboratory studies, 29 field studies	Laboratory studies: Females more dissatisfied: n = 12 No difference: n = 4 Inconclusive: n = 4 Eleven out of 20 studies report that females prefer (significantly) higher temperatures than males, assessed in a range of different thermal conditions. Females are reported to be more sensitive to draft, have lower skin temperatures in the same thermal conditions as men, and be more sensitive to temperature fluctuations in general. Field studies: Females more dissatisfied: n = 16 Males more dissatisfied: n = 1 No difference: n = 10 Inconclusive: n = 2 Generally, females show higher dissatisfaction rate for lower temperatures, are more sensitive to temperature fluctuation and draught. Some studies report different clothing patterns, with women having lower clo values than men.	+
Mishra and Ramgopal, 2013 [59]	20	Non-systematic	Differences between men and women in relation to voting patterns, percentage of dissatisfaction and comfort zone evident. Field and laboratory studies show different clothing patterns between men and women and more inter- and intra-seasonal variations in clothing for females. Most commonly reported differences were those of neutral temperature, with women preferring to be warmer, which is according to the authors due to morphological differences in women (higher surface-to-volume ratio, smaller average body size, less muscle mass, higher surface-to-mass ratio). Women also have a narrower comfort zone according to several cited papers.	+
Rupp, Vasquez and Lamberts, 2015 [60]	8	Systematic, 5 laboratory studies and 3 field studies	Laboratory studies: Mainly in cool temperatures, women are more sensitive to temperature and less sensitive to humidity compared with men. Women more often uncomfortable and dissatisfied with thermal environment than men. Women have lower skin temperatures than men and prefer slightly warmer conditions. Similar neutral temperatures in both men and women and no difference in thermal sensation near neutral conditions. Field studies: in schools, different thermal sensation in girls and boys, over different seasons. Girls more sensitive to low temperatures. During summer, boys more sensitive to higher temperatures. These differences were attributed to the differences in metabolic rate. Other papers state that women are less satisfied with the thermal environment and prefer higher temperatures. Women more sensitive to temperature changes. A study in China showed a 1°C difference in neutral operative temperature between men and women.	+
Wang et al. 2018 [62]	26	Systematic, 11 laboratory studies and 25 field studies	Laboratory studies: Neutral temperature differences were found in two out of eleven laboratory studies. The conclusion is that there is no difference in neutral temperature between men and women. Field studies: Neutral temperature differences were found in seven out of 25 studies. Again, no significant difference in neutral temperature between men and women.	-

Table 5. Summary of literature review related to body composition and fitness as physiological driver of diversity.

Reference, year	No. of papers reviewed by reference (for the specific diversity factor)	Methodological quality of the literature review	General conclusion(s)	Effect of diversity factor on thermal comfort established by review
Wang et al. 2018 [62]	8	Systematic, 4 laboratory and 4 field studies	Laboratory studies: Three out of four exercise studies: significant relationship body size and thermal sensation/thermal comfort in children, overweight children perceiving the temperature to be higher during/after exercise than children with normal weight. Overweight children also exhibited significantly higher rectal temperatures (+0.21°C to +0.30°C) during/post exercise and tended to feel less cold in cool environments than non-overweight children. Field studies: In three field studies, higher BMI (>25kg/m^2) was associated with lower comfort temperature (−0.4°C in Southern Brazil office buildings and −0.7°C in India). Also, people with higher BMI wore less clothing than people with a lower BMI (>25kg/m^2 vs. <25kg/m^2). In a hospital field study, preferred temperature of self-reported frail/less healthy population was higher than preferred temperature of self-reported vigorous/healthier individuals (1.5°C higher in winter and 0.8°C higher in summer).	+

Regarding the effect of physical fitness on temperature perception, a field study in hospitals showed that higher perceived fitness was associated with significantly lower preferred temperatures, and the other way round, people who reported feeling frail and less vigorous preferred warmer environments [81].

Metabolic rate

Of all physiological parameters, metabolic rate is the only one incorporated in the PMV model as input parameter. The metabolic equivalent of task (MET) is one of the standard values in the PMV model (next to clothing insulation, air temperature, radiant temperature, air speed and humidity). MET is a commonly used physiological concept considered a simple procedure for expressing the energy cost of physical activities as a multiple of the basic metabolic rate.[3]

Importantly, absolute metabolic rate is not only determined by activity, but also by other physiological parameters and environmental conditions, such as body composition, diet, adaptation state and temperature. Strikingly, although it is not exactly clear where it is originally derived from, the definition of 1 MET (3.5 ml oxygen/kg/min or 4.184 kJ/kg/h, which approximately equals to 58 W/m^2 where body surface area is 1.8 m^2) is based on measurement of only "*one single 'average' white male person aged 40 years with a bodyweight of 70 kg*" [64]. Recently, it has been indicated that MET might systematically overestimate the metabolic rate in females, as mentioned earlier under diversity factor "sex" [64]. Moreover, also thermal perception of other subpopulations like the elderly and children might thus be inaccurately predicted by the PMV model (also see "age"). The need for a recalibration of thermal comfort models regarding metabolic rate has therefore been stressed earlier [63].

In order to estimate metabolic rate in laboratory and field studies, most studies on thermal perception have applied easy-to-use and low-cost methods, such as activity diaries and heart rate monitors. One review has been identified regarding explicitly the effect of metabolic rate on thermal perception. In their review, Luo et al. [82] underpin the need for more accurate measures of metabolic rate in thermal comfort research, to better understand this relationship (Table 6). Regarding the effect of metabolic rate on subjective perception, Luo et al. [82] report two studies showing that level of activity influences preferred ambient temperature: the more active an individual is, the lower is the preferred temperature.

Physiological adaptation to the thermal environment

It is well established that humans can adapt to a wide range of ambient temperatures. Evidently,

Table 6. Summary of literature review related to metabolic rate as physiological driver of diversity.

Reference, year	No. of papers reviewed by reference (for the specific diversity factor)	Methodological quality of the literature review	General conclusion(s)	Effect of diversity factor on thermal comfort established by review
Luo et al, 2018 [82]	2	Systematic	One study showed that an increased activity level (increased metabolic rate) goes along with lower preferred ambient temperature, e.g. 26.1°C for sedentary subjects, 21.8°C for 25%VO2max exercise intensity, 20.7°C for 40%VO2max exercise intensity. Another study reported that metabolic rate had a more pronounced effect on thermal comfort than the environmental conditions.	+

indigenous people have specialized over the course of thousands of generations to cope even with the most extreme climatic conditions, for example, the Inuits in the Arctic and the Bedouins in the desert [83,84]. A review by Taylor comprehensively discusses the current knowledge regarding genotypical and phenotypical adaptation and thermoregulatory capacities of different ethnicities to specific conditions of the local climate [83]. However, the human body, even without any specific genetic predisposition, can adapt to a broad range of thermal conditions, acutely and in the longer term. When the natural environment fluctuates over different seasons but also over the course of a day and night, physiological adjustments are needed to maintain a stable core temperature and to simultaneously save energy and water resources. Repeated cold exposure, for example, leads to enhanced heat production of the body, whereas repeated exposure to warm environments facilitates more efficient heat loss. Thus, an individual can physiologically become cold or respectively heat adapted.

In order to clarify the use of the word adaptation in the field of thermophysiology and thermoregulation, which might be different to its utilization in the field of thermal perception, a short explanation is given in the following. According to the Glossary of Terms for Thermal Physiology [85], the word adaptation is defined as "*changes that reduce the physiological strain produced by stressful components of the total environment*". Adaptation can be split up in two subcategories, namely genotypic (genetic selection) or phenotypic adaptation. The latter refers to changes of, for example, the thermoregulatory system, and may occur within the lifetime of an organism. Phenotypic adaptation again can be split in two subcategories: 1) acclimation, which is the *experimentally induced* change within an organism, and 2) acclimatization, which denotes the adaptive changes within an organism occurring in response to its *natural* climate. Adaptation processes occur within three broad stages: 1) acute adjustments and physiological accommodation (within seconds to approximately two days), 2) short-term acclimation/acclimatization processes (approximately two days up to two weeks), and 3) full long-term acclimation/acclimatization to the specific thermal environment (as off approximately two weeks, long-term habituation). The reader is referred to a number of publications describing and reviewing acute and longer-term physiological responses to heat and cold exposure, as this is not the focus of this review [86–90].

Habituation of different climatic zones. Regarding the habituation of different climatic zones and its effect on thermal perception, two review papers have been identified. Considering the fact that repeated exposure to a thermal challenge results in physiological adaptation, it seems a logical consequence that also the subjective perception of the thermal environment changes accordingly. Interestingly, in his review from 1973 [58], Fanger claims that "man cannot become adapted to prefer warmer or colder environments". He concludes that "it is therefore likely that the same comfort conditions can be applied throughout the world". However, this conclusion is not unanimously supported by evidence from others. For instance, a later review by Rupp et al. [60] clearly establishes that subjective perception of a thermal environment changes upon adaptation, which is based on the analysis of sixteen original researches (Table 7). Surveys among university students in hot and humid climates (China, India, Indonesia, Malaysia, Brazil, Pakistan) generally indicate that thermal perception is adjusted

Table 7. Summary of literature review related to adaption as physiological driver of diversity.

Reference, year	No. of papers reviewed by reference (for the specific diversity factor)	Methodological quality of the literature review	General conclusion(s)	Effect of diversity factor on thermal comfort established by review
Habituation of different climatic zones				
Fanger, 1973 [58]	6	Non-systematic, laboratory studies only	According to Fanger, there is no effect of adaptation on thermal comfort.	–
Rupp, Vasquez and Lamberts 2015 [60]	16	Systematic, field studies in universities	Inhabitants of hot and humid climates have higher preferred/neutral temperatures and have wider ranges of thermal acceptability. Several studies report better agreement between actual thermal sensation/preferred temperature and predicted votes of the adaptive comfort model (including the running mean outdoor temperature), as opposed to less accurate prediction of the PMV model. Adaptation to local climate (hot and humid) is reported to be especially pronounced in occupants of naturally ventilated buildings, as opposed to air-conditioned buildings.	+
Seasonal adaptation				
Fanger, 1973 [58]	1	Non-systematic	No difference between comfort conditions in winter and summer	–
Mishra and Ramgopal, 2013 [59]	18	Non-systematic	Different neutral thermal sensations for seasons evident when comparing summer and winter season surveys in field studies. Partly, this variation can be explained by variable clothing, but in a number of cases, clothing alone is not sufficient to explain the differences in thermal sensation ($n = 7$).	+
Rupp, Vasquez and Lamberts 2015 [60]	1	Systematic, field study	Different neutral temperatures in fall, winter and spring.	+
Circadian/diurnal rhythm				
Mishra and Ramgopal, 2013 [59]	2	Non-systematic	Two studies from different climatic zones report higher neutral temperatures for occupants during the second half of the day (when usually outdoor temperature and body core temperature is also highest).	+
Wang et al. 2018 [62]	4	Systematic, laboratory studies	Out of four studies, two report significant diurnal differences of neutral temperature with higher preferred ambient temperatures in the afternoon when compared to the morning. In one study, this was even more pronounced in males (+2.4°C) than in females (+0.6°C).	±

to the local climate [60]. For example, one study performed at a university in the subtropical region of Pakistan [91] showed that when the actual sensation vote of survey participants was neutral (thus around 0 on the ASHRAE 55 thermal sensation scale [41]), the PMV model predicted a thermal sensation vote of +1.34. In the same study, a thermal comfort temperature of 29.9°C was reported, which is evidently higher than comfort temperatures reported in studies that were performed in more mild, temperate climates.

Importantly, several papers report that the adaptation to the local climate is more pronounced in occupants of naturally-ventilated buildings than in people usually staying in air-conditioned buildings [92–94]. For example, a study performed in the hot and humid climate of Brazil demonstrated that people who frequently occupy air-conditioned spaces with tightly controlled environmental temperature were less tolerant to dynamic conditions of naturally-ventilated environments and less able to adapt to the local climate [80]. Also, people used to air-condition preferred this type of thermal environment, while people accustomed to naturally-ventilated, free-running buildings preferred not to have air conditioning [92].

Seasonal adaptation. From the perspective of physiological adaptation presented in the above, also a shift of thermal sensation and comfort temperatures over the year may be assumed, at least for those climatic regions, which have distinct temperature differences over the different seasons. In Table 7, information from three review papers is summarized. Strong indications for an influence of season on thermal perception are evident from recent literature, especially from a publication of Mishra and Ramgopal from 2013 [59], who reviewed results from 18 original field studies. Importantly, results from field studies should be interpreted carefully, as part of the variation might be explained by variable clothing.

Diurnal rhythm. Human body temperatures change over the course of day and night in a diurnal (24h) rhythm, with core temperature being at its minimum early in the morning (~05:00 AM) and at its highest in the late afternoon/early evening [95]. It has been hypothesized that also thermal perception is affected by these rhythmic fluctuations of core temperature. Two review papers evaluated the effect of diurnal rhythm on comfort temperature (Table 7 [96,97]). At least half of the studies show significant differences of neutral temperature, with higher preferred ambient temperatures in the afternoon when body core temperature is at its maximum. In one study, this relationship was even more pronounced in males (+2.4 K) than in females (+0.6 K) [62].

Psychological drivers of diversity

Given the definition of thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment" [98], psychological factors can be expected to play an important role in thermal perception. Twelve relevant studies were identified in total. Of all psychological aspects, personal control has received greatest attention in comfort research, as evidenced by nine relevant papers. Other work studied the effect of personality, self-efficacy, and anticipated costs of an action.

Effects of personal control

Paciuk [99] pointed out that personal control can be one of three things (1) available control, (2) exercised control, and (3) perceived control. The effect of available but not exercised control can be considered a psychological aspect, as can perceived control. However, exercised control will change environmental conditions and will be discussed in the section on contextual drivers. Hence, only studies were included that allowed assessment of solely the psychological component of personal control, i.e. studies where environmental conditions were identical in the control and no control condition, or where the outcome variable was the neutral temperature calculated based on thermal sensation votes at different operative temperatures.

Table 8 shows key characteristics and findings of the identified studies. Only outcomes related to thermal perception are considered, and for studies on personal control just those that reflected a purely psychological effect.

Seven out of nine studies found a significant effect of personal control, three of which took place in the field as opposed to a lab setting.

Table 8. Summary of literature review related to personal control.

Authors	Control manipulation	Setting	Participants	Outcomes
Boerstra et al. 2015 [162]	Personal fan vs. recreation of fan usage through experimenter	Lab (office mock-up)	N = 23	**No** effect on thermal sensation, preference, preference, and acceptance
Brager, Paliaga, & de Dear 2004 [163]	High vs low degrees of control over windows	Field (office)	N = 38	**Significan**t effect on neutral temperature in warm season (High control: 23 °C, low control: 21.5 °C) Effect not calculable for cool season
Cao et al. 2014 [164]	Individual heating vs. district heating without control	Field (residential)	N = 24 (in ten apartments)	**Significant** effect on neutral temperature in winter (high control 18.6 °C; no control: 22 °C)
Luo et al. 2016 [165]	No control vs. placebo control	Lab	N = 22	**Significant effect** on TSV and TCV in 4 out of 5 temperatures (more neutral TSV and greater comfort with control)[5]
Luo et al. 2014 [166]	Individual heating vs. district heating without control	Field (residential)	N = 139 households (but in 3 groups, only 2 considered here)	**Effect** on neutral temperature (control: 20.7 °C, no control 18.1 °C)
Schweiker &Wagner 2016 [48]	Individual vs. multi-person set-up	Lab (office mock-up)	N = 36	**Significant** effect on neutral temperature (2 °C difference between highest and lowest PC)
Schweiker et al. 2012 [167]	Control over clothes, windows, shading, fans vs. only clothing	Lab (office mock-up)	N = 21	**Significant effect** on neutral temperature and comfort range (Tn more than 3K lower for no control and comfort range being 6K narrower)
Zhai et al. 2017 [168]	Personally controlled fans vs, experimenter set fans[6]	Lab (office mock-up)	N = 23	**No** effect on thermal sensation votes as a function of effective temperature **No effect** of control at 24 and 26 °C on thermal comfort and preference
Zhou et al. 2014 [101]	No control (but signaling of discomfort) vs. control (activated through same signal)[7]	Lab	N = 15	**Significant effect** on TSV (control vs. none: decrease by 0.4–0.5) and on TCV (control vs. none: increase by 0.3–0.4)

When considering those five studies that reported an effect of personal control on the thermal neutral temperature, the effect was between 0 K[4] and 3.4 K. The mean effect was 2.16 K (SD = 1.28).

Other psychological factors

Three papers considered other psychological factors than personal control: thermo-specific self-efficacy [100], personality [49], and the anticipated cost of cooling [101]. They are each in turn described below.

Hawighorst et al. [100] tested the impact of thermo-specific self-efficacy (specSE), defined as the expectation to be able to execute desired actions with respect to the control of indoor thermal conditions, on the perception of thermal comfort, assumed temperature, perceived control and physiological parameters. A median split on survey responses was used to separate participants into a group with high specSE and low specSE. Data obtained both from a field and a lab study showed that people feel less warm and their thermal comfort is higher if they have a high specSE than a low specSE at comparable temperatures. The lab data also showed that the high specSE group estimated temperature as lower compared to those with a low specSE.

Personality is considered as an individual's pattern of thoughts, feelings, and behaviors that are relatively stable over time and situations. Schweiker et al. [49] analyzed how three of the Big Five personality traits – neuroticism, extraversion, and openness to new experiences – influenced four types of behavioral patterns – clothing adjustments, window opening, blind closing, and interactions with a ceiling fan – and two dimensions of thermal perception – sensation and preference. They also looked at general and specSE. Data obtained from laboratory studies showed that thermal sensation was affected significantly by the trait extraversion, and thermal preference was affected by neuroticism, openness and specSE. Whilst the addition of personality traits to regression models aimed at identifying which factors impacted on the four behavioral actions did not increase the amount of variability explained, it improved the model fit. Auliciems and Parlow [102] also looked at links between personality and thermal perception, and found significant correlations between personality constructs and thermal sensation at work, university and private place of study. However, they used a different measure of personality, the Personality Research Form, which assessed 16 facets on personality; hence, comparing results to Schweiker et al. is difficult.

Zhou et al. [101] tested whether the chosen cooling settings differed when participants had to pay for increased cooling, i.e. they were told their remuneration would decrease. At the same environmental conditions, having to pay the cost of cooling had no significant influence on the occupants' thermal sensation and thermal comfort.

Contextual drivers of diversity

Besides physiological aspects of the human body and psychological aspects, thermal perception indoors is very much determined by contextual factors of the built environment. Stage one of the literature search yielded four relevant review papers dealing with contextual factors and stage two of the review process yielded 20 original papers.

The heat balance approach, such as incorporated in the PMV model, relies on steady state and deterministic effects. However, it is well known that in real-life situations the environmental conditions that humans are experiencing are often varying, sometimes mildly and gradually, such as increasing the heating set-point, but sometimes more extreme and abrupt, for example when entering an air-conditioned building during a hot summer day. Moreover, a building zone's functionality also determines its temperature requirements. For example, Peeters et al. [103] proposed a variant with specified recommendations for each type of room in residential buildings. For example, bedrooms can have a comfort range from 16°C to 26°C. In this part, environmental aspects affecting thermal sensation and comfort are discussed, including local effects and non-uniformities, the influence of control, adaptability, and transient effects.

Local effects and non-uniform environments

Local effects and non-uniform environments affect thermal sensation and comfort and are another source for diversity between persons even when they are staying or working in the same room. From a building contextual perspective, this relates to temperature stratification of the air and radiant asymmetry: two aspects that are highly determined by the type of HVAC systems, the level of thermal insulation of the building envelope, and the control strategy.

A general overview of literature on thermal perception under heterogeneous (non-uniform) and dynamic indoor conditions is provided by Mishra et al. [104] showing that in general, the indoor environment can be variable and acceptable at the same time. At the same time, they summarize that under non-uniform conditions, individual body parts affect whole-body sensation depending on their closeness to the core – body parts closer to the core are associated with a stronger influence.

Halawa et al. [105] discuss the impact of the thermal radiation field on thermal comfort and stress the lack of research on this topic. Their literature review reveals that sample sizes are small, studies are predominantly confined to climate chamber experiments, and results are not consistent. It is important to note that the cited studies often exchange the terms thermal comfort and thermal sensation and, repeatedly, treat them as synonyms. They show that the use of operative temperature as a measure of the combined effect of mean radiant and air temperatures is highly questionable for many cases, especially with respect to radiation asymmetry. Moreover, the radiant field is mostly perceived in the combined form of radiant asymmetry and mean radiant temperature (MRT), which is a result of the asymmetry. However, the PMV's double heat balance equation only accounts for the MRT. Schellen et al. [106] also showed that operative temperature alone is not enough to assess thermal sensation under non-uniform conditions. Thermal sensation of subjects could be well predicted by the PMV model in an experiment with active cooling through convection by mixing ventilation (uniform conditions), but not for the case in which active cooling through radiation by the floor was combined with displacement ventilation.

In addition to these general observations, local effects and non-uniform environments were found to have diverse effects on groups differing by physiological factors. For example, Schellen et al. [107] showed that physiological responses under non-uniform conditions (cooling by radiation) not only differed from responses under uniform conditions (cooling by convection), but also between males and females: Skin temperatures of the males were significantly lower during radiative cooling compared to convective cooling, whereas skin temperatures of the females were significantly higher during radiative cooling compared to convective cooling. Moreover, core body temperature of the females was lower during radiative cooling compared to convective cooling. Whole body thermal sensation did not differ significantly between radiant cooling and convective cooling. At the same time, females' whole body thermal sensation was affected by local thermal sensation of the extremities. Overall, the results indicated that thermal sensation is more affected by radiant asymmetry than by temperature stratification.

Transient effects

Mapping environmental conditions to thermal sensation and comfort requires considering transient effects such as drifts (passive, monotonic, and steady changes), ramps (the same, but actively controlled), cyclical variations (triangular or sinusoidal variations), and step changes.

Several studies have focused on temperature ramps and their effect on thermal comfort including both the effects of the rate of change as the effects of the magnitude (peak to peak) [108–114]. A small steady rate of change (0.5 K/h) is in general not significantly noticeable [108–111], but its effect increases after some time and significantly affects sensation after 3 – 4 hours (depending on clothing) [113]. Interestingly, fast cyclical variations with amplitudes in the order of 1.0 K/h and 1.5 K/h are suggested to allow larger deviations from thermoneutrality compared to slower changes (0.5 K/h) [109], however, this simply may be contributed to a time lag in skin temperature [115]. Hensen [112] concluded from several studies that if the amplitude of the cyclical variation is larger than 1 K, the acceptable temperature range decreases with increasing variation frequency, i.e. larger rate of changes, and the largest acceptable temperature range is under steady state conditions. More recently, Schellen et al. [114] studied the effects of drifting temperatures on young and elderly subjects analyzing both thermal sensation and thermal comfort. They showed that a temperature drift of 2 K/h resulted in slightly decreased thermal comfort compared to constant temperatures, but drifting conditions were still perceived as acceptable.

Regarding step changes, Mishra et al. [116] studied people entering from warm outdoor conditions into a museum conditioned at approximately 21°C. For visitors who had been inside for 20 min or less, the thermal sensation vote had a significant relation with the outdoor temperature but not the indoor temperature. After entering the museum, most people felt warm due to the warm outdoor conditions and perceived the cool indoor conditions as comfortable, but as visitors were longer in the museum, they gradually started feeling cooler and more uncomfortable. In an evidence of alliesthesia, which is a concept that states that the feeling of (thermal) pleasure is highest when a stimulus counteracts (thermal) stress [51,117], the visitors that were inside for twenty minutes or less accepted the thermal conditions, but eventually women started to feel cooler than men. After one hour, the perception of the environment reached a steady state. Parkinson et al. [118] concluded that it is even possible to evoke alliesthesia within the TNZ, which is most representative for the physiological state of building occupants in most indoor environments. Moreover, the thermal stimulus may be cutaneous under mild conditions, and hence, a disturbance in BCT is not required.

Control

Besides the psychological effect on thermal perception as discussed in the previous section on personal control, building control can significantly influence the course of indoor environmental parameters, and hence, occupants' thermal comfort. Recent developments recognize the need to address individual differences by personal conditioning systems that allow to control the micro-environment directly surrounding the occupant [119]. With respect to control, three concepts receive much attention: (1) the human-in-the-loop control, e.g. [120], which gathers occupant' feedback to enhance control performance, and (2) using personal comfort models to tailor the indoor environment to individual needs, e.g. [121], and personal comfort systems [119].

Personal conditioning typically targets local discomfort, and hence, results in non-uniform environments [122]: the hands and arms are critical body parts in cool environments, whereas the head and neck are critical body parts in warm environments. Therefore, the most effective and efficient mechanisms for providing a personalized micro-environment, differ between heating and cooling. Personal ventilation is most effective for cooling while maintaining comfort at room air temperature up to 30°C and relative humidity of 60 – 70% [123]. Also Zhang and Zhao [124] showed that face cooling by elevated airspeed is very effective and maintains comfort up to 30°C air temperature [124]. A study by Pallubinsky et al. [125] supports these findings, showing that increased ventilation in the face region by means of a fan, either alone or in combination with conductive cooling of the underarms, improved thermal sensation and thermal comfort in an ambient temperature of 32°C.

Personalized heating has received less attention in literature [122]. Radiant and convective heating are most effective with respect to personal heating. Comfort can be maintained by chair heating at air temperatures down to 15°C [126] and by radiant floor heating at air temperatures down to 18°C [127].

Clothing adaptability

In addition to physiological adaptive processes described above, the adaptation of clothing is a common and effective strategy by occupants. For example, occupants can tolerate operative temperatures up to 29°C just by adjusting their clothing [11]. Therefore, ASHRAE Standard 55 [41] applies to buildings with operable windows, no or limited operation of mechanical systems for cooling and heating, and in which occupants are allowed to adjust their clothing by at least 0.5 Clo. In addition, research has shown that the clothing insulation level of individuals is adapted to the outdoor and indoor conditions [14,128–130]. Evidence regarding clothing level differences between males and females differs; while Schiavon & Lee [130] report similar clothing insulation levels, de Vecchi et al. [131] state that males' clothing insulation level is less variable than that of females. In addition, the latter show that clothing insulation levels also differ between age groups, with higher age groups wearing clothing ensembles with higher insulation levels.

Discussion of diversity drivers with respect to the prediction of thermal perception

The review results showed several drivers of diversity in the areas of physiology, psychology and context. In this section, we will discuss the extent to which the body of knowledge is sufficient to include these drivers into a model for the prediction of thermal perception.

Physiological differences

Age, sex, body composition and fitness, and metabolic rate

The literature review has shown ambiguous results for age- and sex-related differences, but a clear trend for body composition (weight and BMI) and metabolic rate. Interestingly, resting metabolic rate varies between groups of different age, sex, and body composition [132] and using adjusted metabolic rates for subpopulations were found to improve the prediction of thermal comfort [133]. In addition, body composition leads to differences in body tissue insulation or subcutaneous fat and skin thickness [134,135]. Therefore, one can question, whether it is possible to replicate the diversity and ambiguity found in the literature related to differences in age, sex, and body composition by means of physiological variability in metabolic rate and body tissue insulation.

This question can be assessed through the TNZ model because resting metabolic rate, body tissue insulation, and body surface area can all be adjusted. The resting metabolic rate can be calculated based on research findings incorporating differences due to the physiological drivers of diversity such as age, sex, weight, and height of a person [132]. The maximum tissue insulation can be adjusted for subcutaneous fat and skin thickness [134,135] to discriminate between lean and obese (but not adults vs. elderly) [136,137]. The body surface area can be calculated based on weight and height of a person [138]. The reader is referred to the supplementary materials for detailed equations and exemplary results.

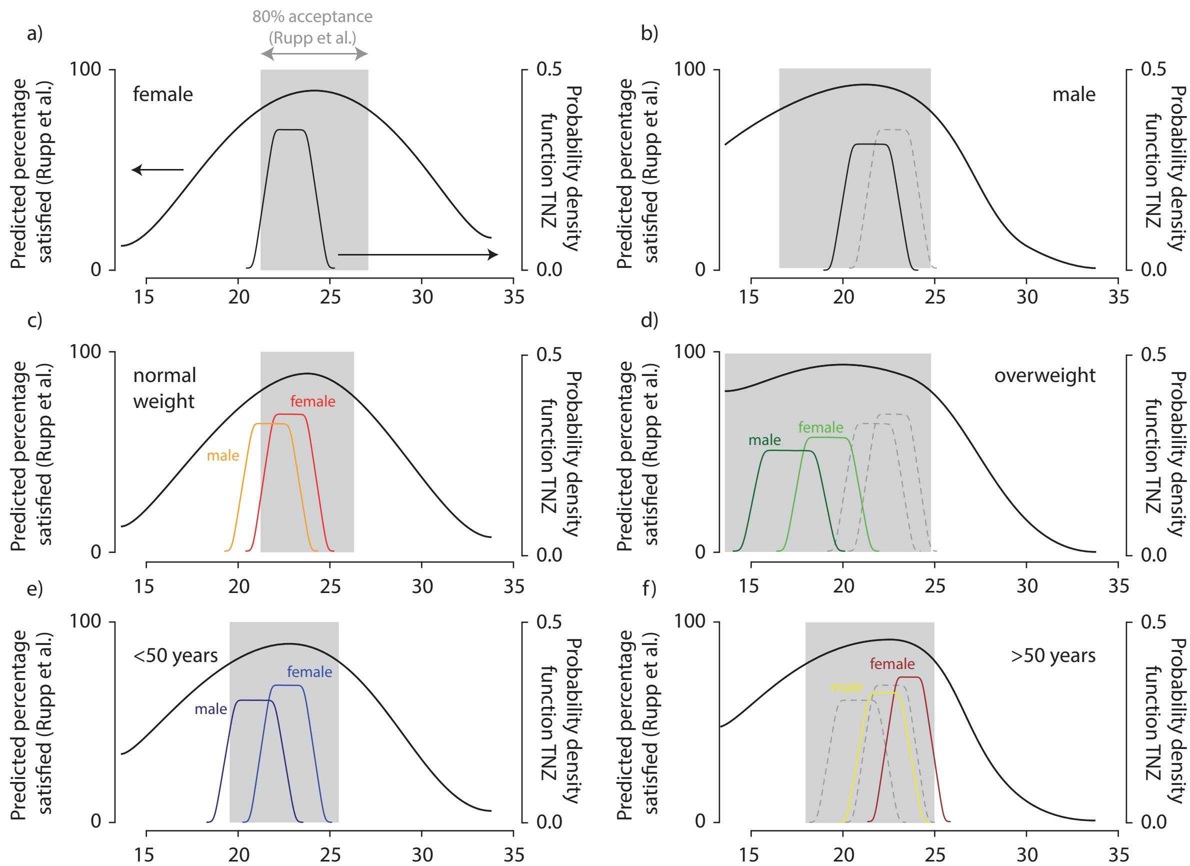

Figure 4. Comparison between findings by Rupp et al. [80] (bold black lines and shaded areas) and the results of the pdfTNZ approach (gray dashed lines are pdfTNZ's from left side of figure to ease comparison).

Figure 4 shows the comparison between the curves for the percentage of satisfied (PPS) presented by Rupp et al. [80] based on a large dataset from field studies in Florianopolis and the pdf_{TNZ} using the mean conditions and physiological characteristics of the dataset by Rupp et al., kindly provided by the authors (see supplement materials for details). It is important to note that the curves presented by Rupp et al. are based on thermal comfort votes and not, as done by Fanger, on transformed thermal sensation votes.

As seen in Figure 4, the pdf_{TNZ} aligns beneath or close to the peaks of the PPS curves from the full dataset of Rupp et al. [80]. For instance, the pdf_{TNZ} for males is shifted to the cold side compared to that for females in a similar way like the PPS curve shifts and the pdf_{TNZ} for males has a wider plateau while the shaded area of 80%-acceptance from Rupp et al. is also wider for males. In addition, the significant shift towards cooler temperatures for obese persons is well replicated. It should be noted, that the pdf_{TNZ} represents solely the mean female and male for each subgroup, while the PPS curve is based on several hundred persons, which differ in their individual characteristics. Therefore, it should not surprise that the range of acceptable temperatures is much wider for the PPS than the range of the pdf_{TNZ}. In addition, the strong overlap between PPS of Rupp et al. and pdf_{TNZ} further suggests the applicability of the TNZ model for aspects related to thermal comfort.

These observations suggest that the diversity due to the factors sex, age and body composition observed in the field can be (partly) replicated by taking into account the diversity in resting metabolic rate and tissue insulation due to physiological characteristics of a person. This could also explain why studies looking at only one of these drivers of diversity, e.g. age, found differences, while others did not find any differences, when these studies do not control for the other two drivers of diversity (in this example sex and body composition). With this respect, the review results by Wang et al. [62] finding around 75% of studies reporting no sex differences can be explained by the overlap of the pdf_{TNZ} for males and females (Figure 4(a,b)). At the same time, the slight shift of the pdf_{TNZ} towards warmer operative temperatures for females might explain the observed sensitivity of females towards cooler conditions.

Physiological adaptation

In addition to physiological characteristics of diversity in thermal perception, differences in the level of physiological adaptation and their effect on thermal perception were summarized above and grouped into adaptation due to habituation of different climatic zones, seasonal adaptation, and diurnal rhythm. It has been established based on the existing literature that habituation of different climatic zones, as well as seasonal changes of the thermal environment, induce *physiological* adaptation, which is also accompanied by *subjective* adaptation of thermal perception. Moreover, preferred temperature has been suggested to change over the course of a day, which is likely due to circadian changes of body temperatures.

The exact physiological processes are still under investigation and by the time of submitting this manuscript, the authors of this review did not find any research intending to implement true physiological adaptive processes into models for the prediction of thermal perception. A first intent can be seen in the approach by Schweiker et al., which adjusts the metabolic rate as input to either PMV [13,14] and/or SET [13] calculation to model effects of physiological adaptation as described in section "Methodology", Equation (2). As a result, the output of the PMV model aligns with the results of the adaptive comfort model [13,14]. It should be noted that Schweiker et al. do not claim that a decrease in metabolic rate is the true process underlying physiological adaptation but use it as a proxy available to adjust the inputs for PMV/SET calculation.

Based on the results of a comprehensive literature review on the physiological aspects of heat adaptation by Taylor et al. [90] and other physiological studies [89,139], it can be assumed that a decrease of metabolic rate in hot environments, which has earlier been suggested to be a physiological consequence of heat adaptation [140], is not due to physiological changes but is rather attributable to behavioral adjustments [90]. However, an enhanced metabolic response to cold exposure has consistently been reported as a result of cold adaptation [141].

The approach by Schweiker et al. can also be applied to the TNZ model by adjusting clothing insulation level and metabolic rate based on the running mean outdoor temperature (T_{rm}). Consequently, the pdf_{TNZ} is shifted towards higher operative temperatures (Figure 5a green line) and

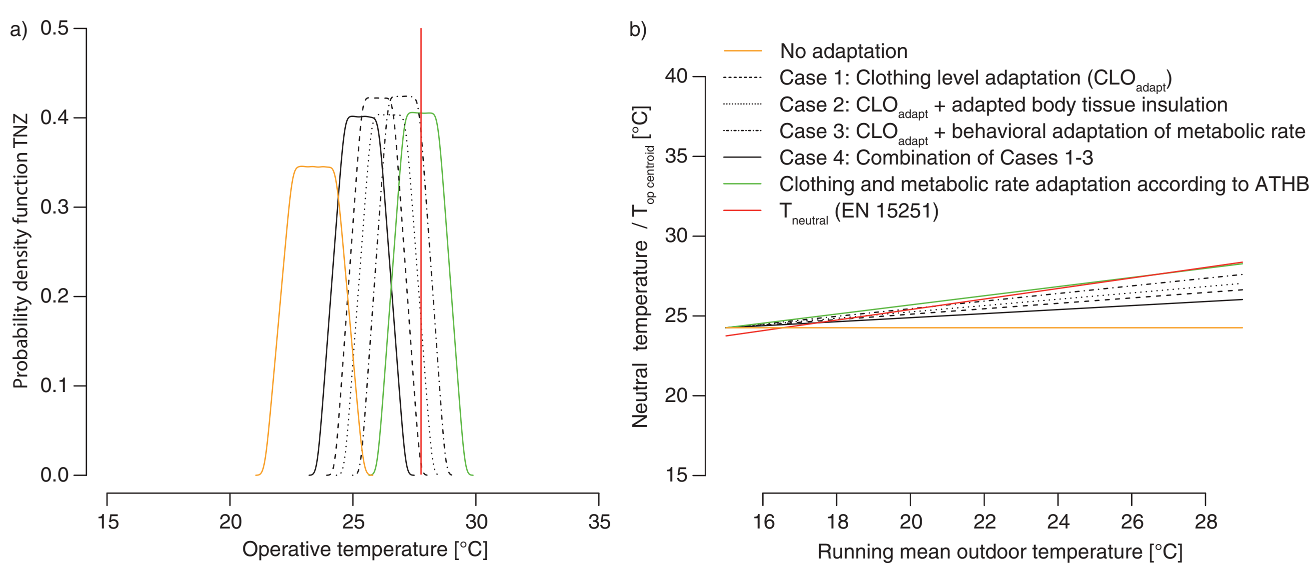

Figure 5. Comparison between adaptive comfort model [43], ATHB [14], and pdfTNZ approach; a) changes in pdfTNZ b) changes in neutral temperature/ Top centroid due to variations in CLO, body tissue insulation, and metabolic rate (see text for details).

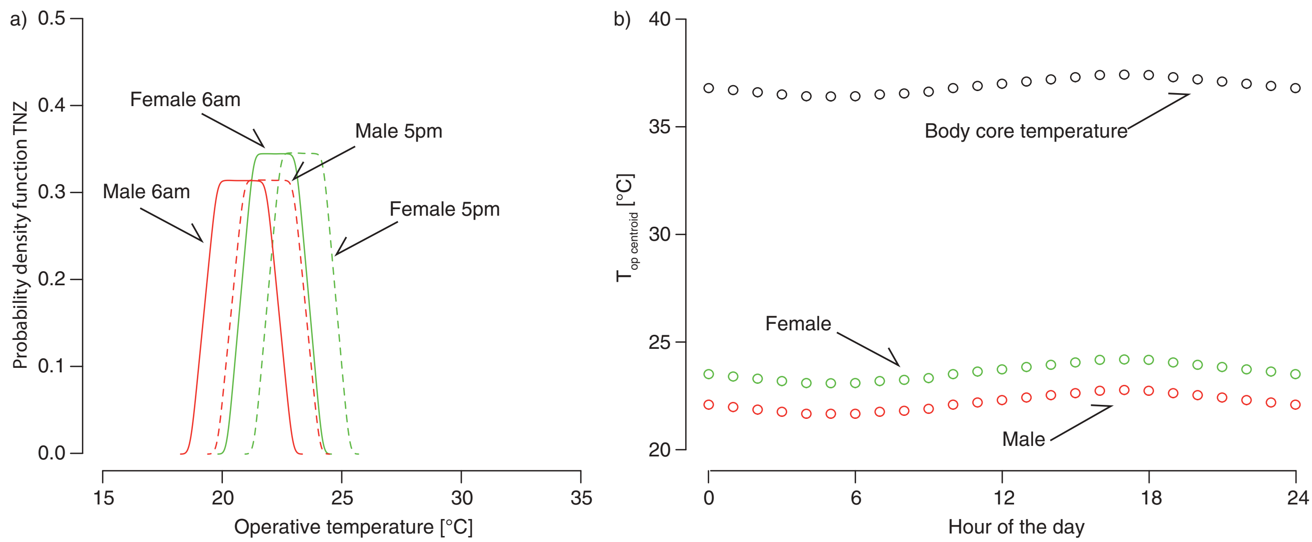

Figure 6. Effect of circadian rhythm of core temperature [144] on pdfTNZ and diurnal pattern of Top centroid.

the $T_{op\ centroid}$ (Figure 5b green line) shows the same trend as the neutral temperature calculated according to EN 15251 (red line).

The TNZ model offers the possibility to adjust other parameters related to heat/cold adaptation than the metabolic rate. For instance, one mechanism of physiological adaptation resulting from heat acclimation/acclimatization is the body's enhanced capacity to dissipate heat [142,143]. To our knowledge, it is not explicitly reported that body tissue insulation is decreased with adaptation to heat, however, from the increased peripheral blood flow resulting from heat adaptation, it is plausible that body tissue insulation decreases. Therefore, to test the effect of this assumption, four cases were calculated using the pdf_{TNZ} approach (see Supplement Materials for details).

- Case 1: adaptation of clothing level with T_{rm} according to the ATHB approach [14];
- Case 2: adaptation of clothing level as in Case 1 and using 10% lower value for the maximum body tissue insulation (0.11) at T_{rm} = 29°C (compared to 0.124 at T_{rm} = 24°C);
- Case 3: adaptation of clothing level as in Case 1 and applying equation by Hori [140] to adjust metabolic rate due to behavioral adaptation
- Case 4: combination of Cases 1 to 3.

Figure 5 shows the effect of such implementation on the pdf_{TNZ} and $T_{op\ centroid}$. The effects on thermal perception are comparable to those postulated by the adaptive comfort model and the ATHB approach. The numbers for tissue insulation used in case of a heat-adapted person could not be extracted from the literature but are assumed values. More research is necessary to establish the relationship between (seasonal) heat adaptation and changes in body tissue insulation as well as core temperature set points for individual sub-populations in order to extract trustable values for the prediction of thermal perception.

In addition to seasonal physiological adaptation, this review listed diurnal differences in thermal perception together with the well documented circadian rhythm of body core temperature [144]. Figure 6 shows the effect of changes in body core temperature on the position of the pdf_{TNZ} and the diurnal pattern of $T_{op\ centroid}$. About 1K difference in thermal perception between the lowest value at nighttime and the highest value in the afternoon can be attributed to such standardized pattern of core temperature variation. In reality, diet-induced thermogenesis as well as different activities can lead to further variations increasing the diversity between individuals.

Differences due to psychological drivers of diversity

The review on psychological drivers describes personal control as one othe most investigated

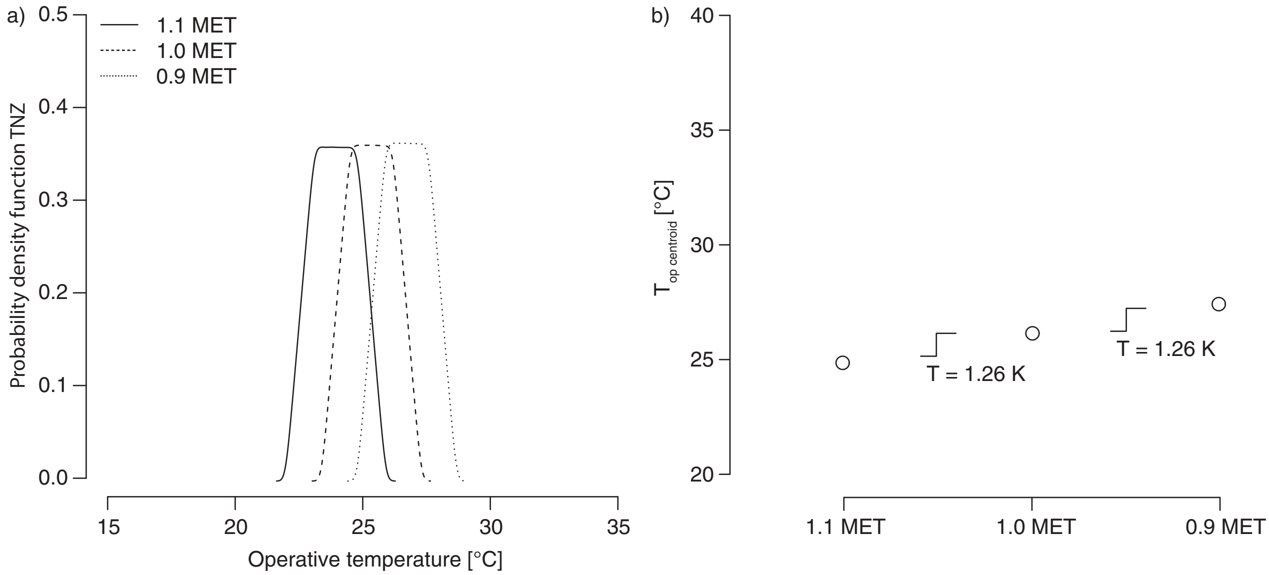

Figure 7. Effect of hypothesized changes on metabolic rate due to diversity in stress levels.

psychological driver with clear effects on thermal perception. However, these studies do not discuss potential pathways or mechanisms how perceived control may affect thermal perception. Therefore, the following section discusses two potential pathways and their ability to replicate the findings related to the effect of psychological drivers.

The ATHB approach adjusts metabolic rate to model psychological adaptation, following the assumption of a relationship between stress level (potentially increased by a lack of perceived control) and metabolic rate [14]. This modelling approach is based on existing literature stating a relationship between the emotional state of a person and its metabolic rate [145–147]. Following such approach, Figure 7 shows the effect of variations in metabolic rate on pdf_{TNZ} and $Top_{centroid}$. The observed effect of increased perceived control leading to differences in thermal perception between 1.5 K and 2.0 K would require a metabolic rate reduction between 0.1 MET and 0.2 MET.

However, a review of the relationship between perceived control, stress, and metabolic rate was beyond the scope of this review and initial searches did not reveal any paper measuring the metabolic rate under different thermal and psychological stressors. Therefore, it remains a hypothesis that perceived control affects thermal perception via a physiological pathway, e.g. by an increased/decreased metabolic rate.

A second potential pathway, which could also explain differences due to a person's personality, is a shift in the interpretation of one's thermal physiological state. Depending on the context (e.g. workplace vs. beach) or personality, a person is satisfied or dissatisfied with the current thermal state. As shown in Figure 8, this leads to a position of actual conditions being at the edge or even outside the area represented by the pdf_{TNZ}.

As shown above, both pathways can replicate the effects of psychological drivers found in the literature. However, further research, combining physiological and psychological measures, is necessary in order to examine the validity of one or both of the pathways described above.

Context-related differences

The review on contextual drivers showed that local effects and radiant asymmetries do affect thermal perception of individual body parts and can affect the overall sensation. No examples by use of the TNZ/ATHB approach is given here, as local effects can be replicated in case the conditions surrounding the human body are known. To look at radiant asymmetries multi-node models, as mentioned in

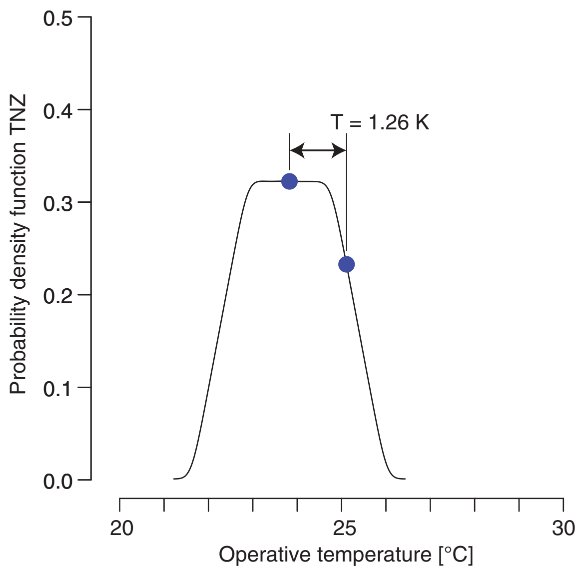

Figure 8. Potential second pathway to explain differences due to psychological aspects. Depending on context or personality, a person is satisfied with conditions at the edge or outside the region marked by the pdfTNZ.

the introduction, should be considered, as those are able to replicate these effects.

The effect of transient environments, such as temperature ramps, is ambiguous. In addition, those ramps found to be perceived and not explainable by a steady-state approach, i.e. ramps with a change >2 K/h, are beyond temperature ramps found in buildings in reality, which are below 1 K/h due to existing thermal mass. Step changes, on the other hand, can inert additional effects such as described by the concept of alliesthesia, which at this point of time cannot be replicated by heat-balance based or thermophysiological models. Models based on neuronal perception are more likely to be able to replicate these effects in the future [26,148]. Alliesthesia should not be dismissed because it is a phenomenon that is probably encountered by most people on a daily basis. To improve our understanding of thermal comfort, which is needed to improve the way we achieve energy-efficient climate control in our buildings, alliesthesia should be rigorously studied, and efforts should be directed towards developing models that are able to include effects such as alliesthesia.

The topic of control, here the effect of control on indoor environmental conditions, and clothing adaptation, which are both drivers of diversity between individuals, are well known and replicable by means of existing thermal comfort models. However, in terms of control, literature looking at psychological effects of perceived control, highlight that the changes in thermal perception due to an exercised control cannot be explained solely by the changes in physical conditions. The modelling approach would therefore be in line with that presented in the previous section looking at psychological differences.

General discussion and conclusions

This review confirms that many different variables have been taken into consideration to explain the vast diversity of thermal perception among humans, as exemplarily demonstrated in Figure 1. In our review, we show that body composition, metabolic rate, adaptation to certain thermal environments, and personal control can be considered as important previously-established drivers of diversity. At the same time, our review shows that literature regarding thermal perception of different age- and sex-groups is inconclusive.

The REA on psychological drivers confirmed that there are only relatively few publications on psychological drivers of diversity. The best researched concept among potential psychological drivers of diversity is personal control. In the present review, only studies were considered with the same environmental conditions or which calculated the neutral temperature. The latter differs by about 2 K between high and low personal control.

The review of contextual drivers summarized evidence regarding the effect of differences in local conditions and radiant asymmetries. The effect of temperature gradients is ambiguous and not related to gradients naturally occurring in buildings.

At the same time, it is clear that the field of research is still far away from understanding many of the underlying mechanisms of individual drivers of diversity, and that there remains a significant amount of unanswered research questions before being able to model those drivers.

Demographic and physiological drivers of diversity

Evaluation of demographic and physiological differences showed that differences between age- and sex-groups, as well as the ambiguity of results related to these drivers, may be explained by differences in resting metabolic rate and body composition. The latter can be replicated by adjusting the corresponding input values for thermal comfort models. Another possible explanation might lie in the evaluation techniques applied in the respective original studies. In the existing literature, it has frequently been stated that although there seems to be no significant difference of neutral/preferred ambient temperature between males and females, and older and younger people, respectively [62], women as well as the elderly are generally more susceptible to changes of temperature, and prone to prefer warmer environments (Table 4) [59,60,67]. Using the pdf_{TNZ} approach, we show that theoretically, there is an overlap of neutral temperatures for males and females, but towards the fringes of the probability density function, this overlap gradually disappears. Hence, there are likely to be temperatures (temperature ranges) at which men are still comfortable, but women are not, and the other way around. The overlap shifts to different temperatures and/or decreases in magnitude with a change of body composition and also with age. This might imply that, for example, an overweight male individual has a distinctly different comfort zone than an elderly female person with a healthy BMI. These differences are, however, difficult to pick up, if a survey is conducted without collecting all relevant variables and at stable thermal conditions.

Therefore, more research in controlled environments and with controlled samples is necessary to confirm these preliminary observations. In addition, there is a necessity for additional studies which collect a variety of drivers of diversity from a large sample in field environments, like the one presented by Rupp et al. [80]. These studies can then be used to challenge these preliminary findings and continue the discussion towards a validated model for the prediction of thermal perception considering the diversity in physiological drivers.

With respect to physiological adaptation, modelling the adaptation of metabolic rate and body tissue insulation can replicate the observations of field studies. However, these adaptive processes are highly speculative and more complex mechanisms are most likely in place. For example, one of the yet unanswered questions is if physiological adaptation occurs simultaneously with subjective adaptation, or if there is a time lag between the two.

Especially for metabolic rate, further studies need to make a clear distinction between behavioral effects on metabolic rate and physiological ones, given the ambiguous findings of field and laboratory studies, especially regarding heat adaptation. In addition, it has been shown previously that the process of physiological adaptation to both heat and cold is highly individual, even in relatively homogenous study populations [88,89,149]. It is likely that physiological adaptation differs even more, for example, between groups with different age and/or body composition. These complex interactions need to be addressed in future studies.

Psychological drivers of diversity

While psychological variability can be replicated by adjusting the metabolic rate or by a shift in the interpretation of the physiological signal, much more research is needed to fully understand what the drivers of psychological variability are and how they exert an influence. Emotion-related variables are likely candidates to be other drivers of psychological variability. For example, a conference presentation by Huebner [150] showed that manipulation of a person's emotional state through recall of happy or sad life events affected thermal sensation in two online surveys, though results were ambiguous for TCV.

Context-related drivers of diversity

The effect of context-related differences on thermal perception, such as radiant asymmetries or step changes, requires more complex modelling approaches than heat balance models. At the same time, effects of building control need to be looked at in more detail to differentiate better between physiological and psychological effects. In this respect, Liu et al. [151] present a grey-box approach to quantify the share of the psychological aspects on differences in thermal perception, by defining all differences of thermal perception not explainable by physical influences as psychological influences. However, this approach requires a clear understanding of all physical and physiological influences on thermal perception, which – according to this review – does not exist yet.

Holistic perspectives

While research on individual drivers is necessary, a bigger task is to look at combined effects of individual drivers, such as physiological and psychological ones together with their interactions. In addition, the global context cannot be ignored. This review has shown that body composition co-determines people's perception of the thermal environment; people with overweight have been shown to prefer cooler environments. In the context of global warming, this leads to a further rise in the cooling demand of buildings, in order to achieve thermal comfort of building occupants, given the fact that obesity prevalence is expected to increase even more in future.

Decreased physical performance in thermally challenging environments is attributed to the increased cardiovascular and metabolic demand for thermoregulation [152], and decreased cognitive performance is for a major part attributed to the distraction and sleep deprivation that can be caused by thermal discomfort [153]. Therefore, for optimal productivity over economic sectors such as manufacturing, construction, transportation, tourism and agriculture, the challenge is to maintain thermal comfortable conditions despite thermal challenges and climatic changes.

Next, the increased mortality associated with thermal extremes occurs primarily in the elderly, who are less able to compensate temperature rises and fluctuations [56], and are (therefore) more vulnerable [154], meaning that negative health consequences due to climatic changes might be exacerbated in this population. Hence, the conservative challenge is to maintain thermal comfort for the elderly, as to minimize their cardiovascular burden that is associated with thermoregulation in hot and cold environments. Noteworthy, in contrast to the conservative challenge, current progressive studies are examining whether "thermal training", by repeatedly exposing people to thermally both uncomfortable warm and cold conditions, can actually make people more resilient to thermal challenges, especially those who are at risk for negative health consequences.

It is of great importance to mention that a solid body of latest evidence has already established that there are health benefits from experiencing dynamic thermal conditions, reaching towards the limits and beyond those temperature ranges regarded as comfortable [87,89,155–157]. Frequent excursions towards warmth and cold, even those of mild nature, have been shown to enhance thermoregulatory capabilities due to acclimation [158]. Moreover, these excursions can evoke positive health effects such as improved glucose metabolism by increased insulin sensitivity [159], and hence, may play a role in mitigating the widespread metabolic syndrome and type 2 diabetes [38].

These findings related to health impacts makes the interactions between people and their thermal indoor environment particularly interesting for studies on human thermal adaptive capacity. Within climate change research, the adaptive capacity is described as the capacity of a society or individual to adapt to future climatic changes [160]. In view of climate change, the above mentioned "temperature training" may provide a viable way to increase our adaptive capacity, or, in other words, our resilience towards more extreme temperatures. Temperature training could be achieved outside of laboratories e.g. by increased/decreased clothing levels in moderate conditions [161]. Being able to model the effect of important individual drivers on thermal perception and related knowledge regarding the boundaries of thermal comfort can serve as a basis to look at variables affecting diversity in the adaptive capacity.

Limitations

In the process of conducting and writing this manuscript, a number of limitations have been identified. Firstly, as the present review is not of a fully systematic nature, relevant publications might have been missed. The latter should be taken into consideration especially regarding demographic and physiological drivers of diversity, as this part of the review only included already existing literature reviews. For example, the existing review publications regarding physiological adaptation and thermal perception was predominantly focused on (sub)tropical conditions but lacked examples for cold environments. Moreover, although original research with respect to thermal perception and comfort in different ethnicities are encompassed in the current review, no study was identified stating explicit information regarding the actual differences of thermal perception and comfort *between* ethnicities.

Secondly, the comparison of review results with implications for modelling is based solely on the combination of TNZ and ATHB approach. The required physiological input parameter "metabolic rate" was estimated by scaling the predicted resting metabolic rate (measured in reclined position: 0.8 MET) to the ASHRAE MET equivalent corresponding to resting/seated activity. It is not known how the scaling influences the error of the metabolic rate production. Furthermore, the second physiological input parameter, "body tissue insulation", lacks dedicated papers that identify how the characteristics of this variable varies over subpopulations. Therefore, the influence of changes in body tissue insulation on the modelling outcome has to be interpreted with care. In addition, using the height and weight of a person to estimate resting metabolic rate lacks the possibility to distinguish between persons with a higher weight due to a high degree of muscular tissue from others. Assessing variables related to the fitness level of persons in future studies is therefore recommended.

Conclusions

In conclusion, there is a huge variety of potential drivers of diversity and much more research is required to understand better the underlying mechanism of diversity. This information is required in order to rule out irrelevant factors and in particular to reveal the important and significant drivers of diversity. Knowing the true drivers of diversity will be helpful in preparation for global challenges because the indoor thermal conditions chosen by an individual do not only affect the energy use – in itself a driver of climate change – but also affect health, wellbeing, and productivity.

Nomenclature

AC	Air-conditioned
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
ATHB	Adaptive Thermal Heat Balance model
BCT	Body core temperature
BMI	Body Mass Index
CLO	Clothing insulation level
CLO_{adapt}	Adapted clothing insulation level
dTNZ	Distance (of actual operative or skin temperature) to Thermoneutral Zone
HVAC	Heating, Ventilation and Air Conditioning
MET	Metabolic Equivalent of Task
MET_0	Reference MET
MET_{adapt}	Adapted Metabolic Rate
MRT	Mean Radiant Temperature
NV	Naturally Ventilated
pdf	Probability density function
pdf_{TNZ}	pdf of solutions in which BCT falls within TNZ
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PPS	Predicted Percentage of Satisfied
REA	Rapid Evidence Assessment
SD	Standard Deviation
SET	Standard Effective Temperature
specSE	Thermo-specific Self-Efficacy
TCV	Thermal Comfort Vote
TNZ	Thermoneutral Zone
T_{op}	Operative temperature
$T_{op\ centroid}$	Top in the center of the TNZ
T_{rm}	Running Mean Outdoor Temperature

Notes

1. In this review and in contrast to the theory behind the adaptive comfort model [3], psychological variables included are not split up into cognitive-emotional and behavioral ones as we consider them as intertwined, e.g. our change in our cognitive state might change our behavior but a change in our behavior can also impact on our cognitive-emotional state.
2. The reader is invited to test this by using the empirical equation for resting metabolic rate from Roza and Shizgal [132], and body surface area from Dubois and Dubois [138]. For example, comparing a 20-year old female and male with height of 167 cm

(female) vs. 186 cm (male) and a weight of 60 kg and 82 kg, respectively, the resting metabolic rate (scaled from 0.8Met to 1.0Met) is 26% lower for the female without considering body surface area (83 W vs. 113 W), and still 17% (50 W/m^2 vs. 60 W/m^2) when considering the difference in body surface area (1.67 m^2 vs. 1.87 m^2).

3. Note that the association of how activities relate to MET differs in the primary sources for the physiology and built environment research communities (respectively: Compendium of physical activities [169,170] and ASHRAE standard 55). For example, sleeping is defined as 0.9 MET by the Compendium of physical activities, but as 0.7 MET by the ASHRAE metabolic rates for typical tasks and light office work as 1.2 MET for the former and 1.0–1.2 MET for the latter (Table 5.2.1.2 – ANSI ASHRAE addendum to ANSI/ASHRAE standard 55–2010 [41]). This review will use the definition according to ASHRAE.
4. This includes the study by Zhai et al. which did not report the thermal neutral temperature, but reported that no effect of effective temperature on TSV were found, which was here counted as a 0°C difference in neutral temperature.
5. The analysis did not consider the repeated measurement design but employed independent t-tests for comparison which carries an increased risk of false positive results.
6. At 24 and 26°C settings the subject chosen and experimenter provided conditions were basically identical. In addition, regression of thermal sensation votes against temperatures provided.
7. Only answers before an actual change in conditions occurred were analysed.

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Disclosure statement

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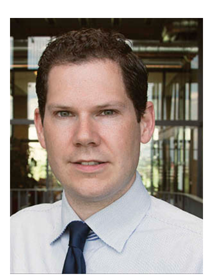

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