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Subjective information in thermal comfort evaluation methods: A critical review

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ABSTRACT

Thermal environments hold significant importance in human living environments, affecting quality of life, work efficiency, and building energy consumption. Accurate evaluation of thermal comfort involves the quantification of subjective information and the establishment of indices and models. Although various thermal comfort evaluation methods currently exist, the complexity of subjective emotions has often been overlooked. This review provides a comprehensive analysis of the underlying purposes and logic behind different thermal comfort evaluation methods, focusing on the intricacies of subjective information. It emphasizes that while substantial studies have already demonstrated that thermal sensation alone is insufficient for evaluating thermal environments in different contexts, there is still an overreliance on thermal sensation by various indices and models. By critically reviewing the role of subjective information in these methods, this review aims to promote the healthy development of thermal comfort evaluation.

1. Introduction

Thermal environment significantly influences occupant satisfaction, productivity, health, and is closely tied to building energy consumption. One of the primary objectives in establishing a thermal environment is to maximize occupant comfort and health while minimizing energy waste [1]. Accurately assessing how comfortable individuals feel within a specific thermal environment, using straightforward and effective methods, is crucial in thermal comfort research.

1.1. Subjective perception

Thermal perception is a complex subjective process influenced by environmental, physiological, and psychological factors. Subjective perception itself is also multidimensional and complex [2]. Thermal sensation, comfort, acceptability, and preference can be regarded as different dimensions of subjective thermal perception [3,4].

Thermal Comfort and ***Thermal Sensation*** are the most common concepts in thermal environment evaluation. It wasn't until the latter half of the 19th century that people realized that Cold and Warmth are separate human sensations. Subsequently, as interest in the thermal environment grew, ***Thermal Sensation*** became the most common subjective perception in thermal environment evaluation. ASHRAE-55-2023 defines thermal sensation as "*A conscious subjective expression of an occupant's thermal perception of the environment* [5]." Some researchers suggest that thermal sensation primarily reflects a person's subjective evaluation of the state of the body's thermal receptors [6]. ***Thermal Comfort*** was not recognized as a measurable entity by heating and ventilating engineers until the early 20th century [7,8]. It is defined by ASHRAE standard 55–2023 as "*that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation* [5]." In 1967, Gagge et al. described it as "*a recognizable state of feeling*" and stated that "*it is usually associated with conditions that are pleasant and compatible with health and happiness; and discomfort with pain which is unpleasant* [9]." Subjective perception is an important dependent variable in thermal comfort evaluation and sometimes the only dependent variable. Accurately understanding, defining, and quantifying subjective perception is crucial for subsequent research[3]. Although many studies have highlighted the complexity of subjective perceptions in thermal comfort, this issue has yet to receive a systematic review. While numerous reviews have summarized related indices and models in thermal environments, approaching the topic from the perspective of

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"comfort evaluation" may offer new insights into the field.

1.2. Methods for thermal environment assessment

The evaluation of thermal comfort in human living environments primarily concerns human perception. The most direct method to obtain subjective feedback from individuals is through direct voting. However, the assessment of indoor thermal environments is typically used to guide the design and operation of buildings and HVAC systems. In most practical scenarios, creating comfortable environments without real-time feedback is preferred. In such cases, predicting individual thermal perception based on influencing factors is essential, leading to the development of various indices, models, and theories.

Over the past century, researchers have developed numerous predictive indices and models for thermal comfort assessment. As of now, at least 165 indices have been established [10,11]. In the early 20th century, assessment indices for thermal environments primarily aimed at preventing thermal injuries during military training or outdoor work in extreme weather conditions. As a result, the earliest established indices were heat risk related indices [10,12]. Heat risk indices typically consider the influence of temperature and humidity, predicting outcomes related to cold and heat stress. For example, Wet Bulb Globe Temperature (WBGT) [13] emerged from this need, integrating dry bulb temperature, wet bulb temperature, and globe temperature to evaluate thermal stress and heat injuries.

Guan et al. indicated that a comprehensive thermal comfort model typically comprises three parts: a detailed multi-segment, multi-layer physical heat exchange model incorporating clothing interactions between the human body and environment; a multi-segment physiological temperature regulation model simulating the passive and active heat systems of the human body; and a psychological thermal sensation model predicting local and whole-body thermal sensations [14,15]. Among these, the most representative and widely used is the Predicted Mean Vote (PMV) model developed by Fanger [62], which predicts thermal sensation based on human thermal balance and simplified temperature regulation calculations. Multi-segment physiological temperature regulation models have also matured, including Stolwijk's multi-segment physiological model [16], Gagge's two-node model [17], and later Fiala's multi-segment multi-node model [18,19].

Since the introduction of the adaptive concept in the 1970s, there has been increasing attention to individual differences (such as gender, age, etc.) and their perception in various environments (such as building types, ventilation methods, climate, etc.). This theory emphasizes the importance of contextual factors. This theory emphasizes the importance of contextual factors, which is why current thermal comfort research adopts different evaluation methods for specific scenarios.

Advancements in automation and related technologies have facilitated the development of models that predict thermal sensation by directly monitoring physiological parameters. Studies on behavioral patterns have advanced concurrently to assess the relationship between human perception and environmental parameters, particularly in applications related to environmental control or energy consumption simulation.

Although several reviews on thermal comfort models exist, few have delved deeply into the subjective information they incorporate. Most of the indices and models can be categorized into six types based on their foundational logic (see Fig. 1), with a significant reliance on subjective voting. The following sections will further explore these models and the role of subjective information within them. Section 2 reviews the differences and methods of quantifying subjective information in thermal comfort. Section 3 outlines classic thermal comfort indices, emphasizing their evaluation logic and predictive goals. Section 4 introduces other assessment models and theories, focusing on the subjective information they account for.

2. Subjective perception information

Obtaining quantified data that accurately reflects subjective perceptions is crucial for thermal comfort assessment and subsequent environments design and control.

2.1. Subjective votes

"You cannot manage what you cannot measure; the first step to maintaining a good thermal environment is to accurately measure it" [4,20]. Questionnaire is a straightforward and practical method to objectively quantify subjective perceptions. Therefore, in the process of thermal comfort assessment, the first step is often to determine appropriate voting types, which serve as the foundation for developing indices and models related to thermal perception and form the basis for subsequent research on thermal environment issues.

There are various types of votes related to thermal perception, including thermal sensation, thermal comfort, thermal preference, thermal acceptability, and thermal satisfaction. A study has summarized the types of relevant votes and described their scales [21]. Table 1 presents some commonly used descriptions. Additionally, studies focusing on perceptions of factors such as air velocity [22,23]and humidity [24,25] also utilize relevant votes. Among these methods, Bedford's structured interview technique, frequently employed in research, combines thermal comfort with sensation into a single one-dimensional

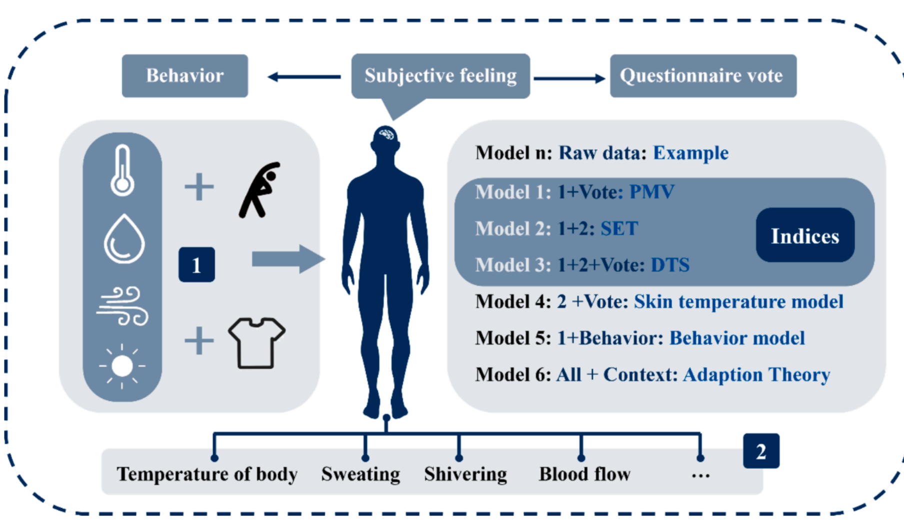

Fig. 1. Overview diagram of thermal comfort evaluation methods.

Table 1
Description of vote.

Vote type	Vote Description
Thermal sensation [5]	Cold, cool, slightly cool, neutral, slightly warm, warm, hot
Thermal comfort [27]	Comfortable, slightly uncomfortable, uncomfortable, very uncomfortable
Thermal preference [28]	Cooler, no change, warmer
Thermal acceptability [28]	Acceptable, not acceptable
Thermal pleasure [29]	Very unpleasant, unpleasant, slightly unpleasant, indifferent, slightly pleasant, pleasant, very pleasant
Bedford scale [26]	Much too warm, too warm, comfortable warm, comfortable neither warm nor cool, comfortable cool, too cool, much too cool

scale. Unlike the use of both the Thermal Sensation Vote and the Thermal Comfort Vote, this method does not differentiate between the two feelings. For example, it cannot provide information on situations where a person feels thermally neutral but not comfortable [26].

2.2. The insufficiency of thermal sensation

Different vote types provide distinct insights into how humans perceive thermal environments. For instance, thermal preference voting and thermal sensation voting are frequently used in HVAC system control [4] because they straightforwardly express people's demands for air conditioning systems. However, obtaining feedback information directly applicable to temperature control from thermal comfort and thermal satisfaction voting is more difficult. Yet, it is important to note that studies have shown that thermal sensation voting alone cannot reflect whether people are satisfied, comfortable, or pleased with the thermal environment [3,30]. Rather than focusing solely on thermal neutrality, achieving satisfaction, comfort, and pleasure is ultimately the goal of creating a human habitat environment. Thus, there remains a gap between "**convenient for practical engineering applications**" and "**satisfying the real needs of occupants**".

Substantial evidence from different aspects further confirms that thermal sensation alone does not adequately represent human feelings toward the thermal environment. First, people's preferences may not align with neutral sensations. Humphreys et al. emphasized that inquiries into people's perceptions of the thermal environment should not only focus on thermal sensations but also inquire about the desired thermal experience [30]. For example, in summer, people tend to prefer a slightly cooler sensation than neutral, whereas in winter, a slightly warmer sensation is typically preferred [31,32]. Designating thermal comfort ranges based on thermal sensation indices or guidelines fails to reflect actual user preferences in specific scenarios.

Second, thermal comfort is not solely about avoiding too hot or too cold; people experience separate sensations for various stimuli influenced by multiple factors. Studies indicate that thermal affect is impacted by different environmental parameters under different climatic scenarios [3].Yang et al. found that even under thermally neutral conditions (as measured by TSV), factors such as cool airflow from air conditioning, excessive humidity, or inappropriate clothing can decrease comfort (as measured by TCV) [33]. Xie et al. pointed out when comparing natural wind and different types of mechanical airflow, the evaluation of wind comfort should focus on the tactile stimulation effects of wind speed rather than its effects on heat exchange [34]. Research indicates that clothing's impact on comfort is complex, encompassing sensory experiences such as fabric feel, covered areas, and breathability [35–37]. Humidity affects heat loss, thereby influencing thermal balance and sensation, while also producing sensations of dampness and sweating, and affecting people's perception of air quality, thus affecting comfort and satisfaction [24,38]. Additionally, controlling airflow velocity and adjusting clothing are important adaptive behaviors [39], and the power to control them affects people's psychological activities, further influencing their satisfaction with the environment [40]. These research findings prompt us to reconsider whether it is reasonable to solely rely on thermal sensation to recommend comfort ranges [5,41]. This approach overlooks discomfort caused by factors in neutral environments and the broad range of acceptance under non-neutral conditions.

Finally, people's thermal perceptions can vary significantly across different contexts. When entering the field of outdoor thermal comfort, insufficiency in thermal sensation becomes more pronounced [3]. While extensive literature addresses neutral ranges for outdoor thermal environments across various climatic zones, such studies may not guide urban planning effectively due to disparities between outdoor thermal comfort and neutrality. People tend to have a broader acceptance of outdoor environments, with a wider comfort range [42–44]. Many studies suggest that the differences between indoor and outdoor environments are largely due to the dynamic changes in natural wind, solar radiation, and the non-uniformity of the thermal environment outdoors [42,45]. Furthermore, differences in usage scenarios between indoor and outdoor settings and the diversity of environmental conditions contribute to the broader outdoor thermal comfort range. Aside from essential outdoor workers, the primary purposes for being outdoors, such as leisure, socializing, and exercise, may lead individuals to pay less attention to thermal sensation [46]. Natural experience has been proven to mitigate stress and promote positive emotions [47]. As a crucial component of natural environments, natural thermal environment await further exploration regarding their impact on psychological aspects [48,49]. In these cases, physiological sensation is no longer the main focus of thermal environment assessment; instead, psychological characteristics, influenced by more factors, should be further studied. The involvement of environmental psychology may provide valuable insights into the various differences.

2.3. The complexity of questionnaire

In addition to the types of votes, the different expressions and the continuity of options for the same vote can also influence results. For example, even the point numbers and continuity of the TSV alone may affect outcomes. Schweiker et al. [50] have clearly indicated that human perceptions on scales are not equidistant, and whether the scale is continuous can affect the relationship between environmental temperature and sensation voting. The unified description of the TSV scale in ASHRAE-55 has provided great convenience for comparison across different studies. However, the use of a seven-point scale to quantify thermal sensation is partly due to this being the maximum number of points that can produce outcomes reliably understood by different subjects. Although large datasets can ensure statistical comparability, it is challenging to achieve a consistent understanding of each point among individuals. Although it is not the focus of this paper, it is important to note that many regression analyses assume equal temperature intervals between scale levels, which is not the case in reality [50,51].

Another crucial aspect is the influence of language. Subjective voting is based on psychometrics of language; thus voting results are often influenced by language, cultural background, environmental psychological aspects, and other factors [2,51]. For example, in the Japanese and Korean scales, the adjectives used to describe "warm" (+2) and "cool" (−2) carry positive connotations [51,52]。When translated into Arabic, the lack of differentiation between "cool" and "cold" in everyday Arabic vocabulary resulted in a changed range on the thermal continuum compared to the English version [53]. With the establishment of global thermal comfort databases [28], many studies compare data obtained from different countries horizontally. Differences due to language, culture, and other factors should be carefully considered; otherwise, it is challenging to determine whether discrepancies in results across different countries stem from translation ambiguities in questionnaires or adaptations to local thermal environment. The cross-national dataset established by Schweiker et al. has paved the way for addressing this issue [54]. However, researchers from different language backgrounds do not provide detailed descriptions of the original language versions of questionnaires or scales in their articles; instead, they only offer simplified information translated into English. Furthermore, all voting results in global databases are integrated according to their English versions. These "default practices" disregard the potential impact of language and cultural differences on the analysis of thermal comfort data, hindering in-depth analyses related to language, culture, economy, and scales.

3. Indices

It is unrealistic to rely on actual questionnaire feedback to evaluate the thermal environment during the preliminary design and automatic control processes of air conditioning systems and the like. Therefore, models and indices that predict subjective perception based on directly measurable objective data have been developed. Each index or model has its underlying logic and prediction goals. For instance, the widely used PMV model predicts human thermal sensation through an empirical regression formula based on body heat storage, metabolic rate and thermal sensation votes [55,56]. Based on this logic, this section selects widely applied and representative indices, providing a detailed review of their fundamental principles and prediction goals, while discussing issues that merit further exploration.

Indices can be classified into three categories based on their development logic, which are introduced in the following part. The first category includes equivalent temperatures that assign different weights to various environmental factors affecting human heat dissipation. The second category comprises equivalent temperatures that calculate physiological states in detail through thermophysiological models. The third category consists of subjective sensation prediction indices. A summary of the core content of different indices is provided in Table 2.

3.1. The goals and cores of indices

The earliest established indices are Equivalent Temperatures that do not involve thermophysiological models but instead simply integrate environmental parameters based on their impact on human heat dissipation. Due to the similarity in the development logic and objectives of these indices, this section discusses only the commonly used Operative Temperature (T_{op}) and Wet Bulb Globe Temperature (WBGT).

3.1.1. Operative temperature

Operative Temperature is a widely used composite thermal environmental index that involves only three measurements: air velocity, air temperature, and mean radiant temperature. The fundamental principle behind its establishment assumes a person is in a uniform black enclosure, where they exchange sensible heat through radiation and convection with the same amount of those in the actual environment. The uniform air temperature within this enclosure is defined as the Operative Temperature [8,64,65].

3.1.2. Wet bulb globe temperature

Similar to T_{op}, WBGT is also calculated using environmental parameters, but it further considers latent heat dissipation and was developed with the purpose of defining "*the conditions under which heat injury may occur in basic and advanced trainees and to develop safe limits for physical exertion in the heat that will control casualties*[57]." WBGT was initially developed to simplify the cumbersome procedure of calculating Effective Temperature (ET). ET, based on empirical indicators obtained from laboratory research, was first established by Yaglou and Minard, who then introduced the influence of radiation to create ETR (effective temperature including the radiation component). Eventually, WBGT was developed after resolving complex calculations using wet-bulb temperature, globe temperature and dry-bulb temperature. The design of the three weighting factors considers environments “that are warm enough to induce sweating” [13,57].

Researchers have introduced human thermophysiological models on the basis of the equivalent concept to replace previous simple passive heat exchange calculations. The purpose of these indices is to synthesize complex environmental conditions into a comparable equivalent temperature based on physiological status. As illustrated in Fig. 2, the calculation of equivalent temperature first requires defining a standard reference environment and selecting physiological parameters for

Table 2
Details of indices.

Indices	Reference	Thermophysiological models	Reference condition	Equivalent indicator	Equivalent meaning	Input*	Output
Equivalent temperature based on heat exchange							
T_{op}	[8]	/	Black enclosure with uniform temperature	Sensible heat exchange	/	T, R, V	Temperature equivalent
WBGT	[13,57]	/	/	Sensible and insensible heat exchange	Heat related injuriesheat stress	T, H, V, R	Temperature equivalent
Equivalent temperature based on thermophysiological models							
SET	[58]	Gagge-two-node model	$T_a = T_{mrt}$, RH = 50 %, Still air, 1.0met, Iclo = 0.6clo	Skin temperature and wettedness	Heat exchange, thermal sensation	T, H, V, R, C, M	Temperature equivalent
UTCI	[19,59,60]	Fiala-UTCI model	$T_a = T_{mrt}$, RH = 50 %, V_a = 0.5 m/s (10 m above ground)	14 parameters related to thermal state**	Heat exchange, Thermal sensation, Thermal stress	T, H, V, R	Temperature equivalent
PET	[61]	MEMI model	$T_a = T_{mrt}$, Water pressure = 12 hpa, V_a = 0.1 m/s, 80 W (light activity) added on basic met, I_{clo} = 0.9 clo	Skin temperature, core temperature	Thermal budget	T, H, V, R	Temperature equivalent
Thermal sensation models							
PMV	[62]	/	/	Metabolic, heat load	Thermal sensation	T, H, V, R, C, M	Thermal sensation
DTS	[63]	Fiala-model	/	Skin temperature, core temperature	Dynamic thermal sensation	T, H, V, R, C, M	Thermal sensation

* In this table, the specific input forms of parameters are not deeply explored; rather, only whether the index considers the following 4 environmental factors and 2 personal factors is discussed: T air temperature, H humidity (including wet bulb temperature, relative humidity, vapor pressure etc.), V air movement (including air velocity, air speed, convective heat transfer coefficient etc.), R radiant (including mean radiation temperature, global temperature etc.), C clothing insulation, M metabolic rate.

**14 parameters related to thermal state: Calculated values of Rectal temperature, Mean skin temperature, Face skin temperature, Sweat production, Heat generated shivering, Skin wittedness, Skin blood flow at 30 and 120 min.

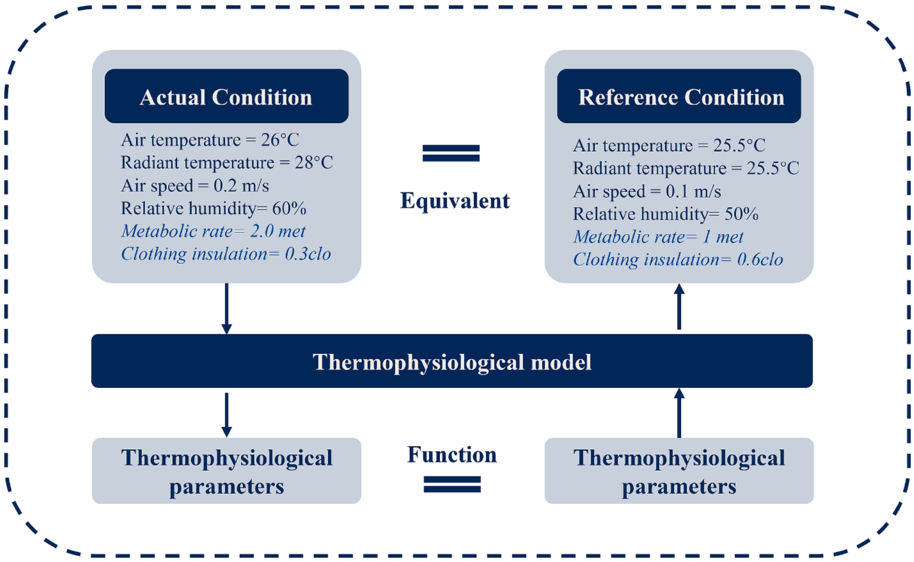

Fig. 2. Calculation logic of equivalent temperature based on thermophysiology models (using reference condition of SET as an example).

equivalence assessment. By employing thermophysiological models, physiological parameters are computed for the actual conditions and simultaneously for the reference conditions. The air temperature in the reference condition, where these physiological parameters are equal (either numerically or through the function of physiological parameters), serves as the equivalent temperature for the actual condition. It is important to note that different equivalent temperature indices utilize different reference conditions (see Table 2), thus comparisons of absolute values between different indices should be approached cautiously. The thermophysiological models used, selection of physiological parameters, and functions used when physiological parameters are considered equal also vary among different indices; detailed specifics are outlined in Table 2 and the subsequent detailed interpretations of each index.

3.1.3. Standard effective temperature

The thermophysiological model used in the calculation of SET is Gagge's two-node model, where skin temperature and skin wettedness are calculated by inputting environmental parameters such as temperature, air velocity, humidity, and radiation, along with personal parameters like metabolic rate and clothing insulation. Simultaneously, physiological parameters are also computed for a standard reference condition. By iteratively correcting the air temperature (with other values fixed) of a reference environment using a difference function based on physiological parameters between two environments, the final output, SET, is the air temperature of the reference environment where the skin temperature, skin wettedness, and total heat exchange equal those of the actual environment [66].

3.1.4. Physiological equivalent temperature

PET is frequently used in outdoor studies [12]. The calculation logic and results of PET are highly similar to those of SET. The key difference lies in the use of the MEMI model (also based on Gagge's two-node model) for its thermal physiological calculations. The equivalent indicators are changed from skin temperature and skin wettedness to skin temperature and core temperature. To simplify the input variables, the clothing insulation is set as a default value of 0.9 clo, and the metabolic rate is assumed to be increased by 80 W above the basal metabolic rate for light outdoor activity [61].

3.1.5. Universal temperature climate index

UTCI was developed under the European COST Action 730 initiative aimed at establishing a universally applicable thermal comfort index [67]. The thermal physiological model utilized for UTCI calculations is based on Fiala's multi-node model, known as the UTCI-Fiala model [19]. For practical application, an Adaptive clothing outdoor model [68] is employed to substitute actual clothing insulation, assuming outdoor conditions with a walking metabolic rate of 1.1 m/s as the default. Environmental parameters considered include temperature, radiation, humidity, and air speed. To use meteorological data for calculation, the input value for air speed is typically the speed measured at a height of 10 m above ground level. The model includes a correction for air speed on the height of the body.

The UTCI equivalent calculation employs representative physiological response parameters. Additionally, UTCI accounts for the influence of exposure duration by utilizing seven physiological variables–rectal temperature, mean skin temperature, face skin temperature, sweat production, heat generated by shivering, skin wettedness, and skin blood flow–combined into a response index computed over 30 min and 120 min. The binary search (bisection) algorithm is employed to determine the reference environmental temperature corresponding to this index as UTCI [69].

Calculating thermal sensation directly rather than using equivalent temperatures is a direct and effective method for thermal environment assessment, however, ensuring model accuracy can be challenging.

3.1.6. Predicted mean vote

PMV, as a direct thermal sensation prediction model, differs fundamentally from equivalent temperatures. The heat exchange between the human body and the environment is firstly calculated. The values of each term in heat exchange equation are determined empirically, and then the human thermal load $\boldsymbol{L}$ is computed. PMV calculation assumes that the mean thermal sensation vote $\boldsymbol{Y}$ is only related to the metabolic rate $\frac{\boldsymbol{M}}{\boldsymbol{A_{DU}}}$ (per unit skin are) and the thermal load $\boldsymbol{L}$.

$$Y = f(L, \frac{M}{A_{DU}}) \quad (1)$$

Assuming $\boldsymbol{L} = 0$, then $\boldsymbol{Y} = 0$, Eq. (2) was established based on actual thermal sensation votes at four different metabolic levels.

$$\frac{\partial Y}{\partial L} = 0.352e^{-0.042(M/A_{DU})} + 0.032 \quad (2)$$

Integrate this equation and substitute heat exchange equation into $\boldsymbol{L}$ to obtain the calculation formula for PMV.

In Eqs. (1) and (2), $\boldsymbol{Y}$ is the mean thermal sensation vote, $\boldsymbol{L}$ is the human thermal load, $\boldsymbol{M}$ is for metabolic heat production, and $\boldsymbol{A_{DU}}$ is the body surface area.

3.2. One size fits all

The original data used to develop these classic indices define their specific application scenarios. For example, PMV was derived from data collected in artificially controlled environments, and when the context changes, people's subjective perceptions can vary significantly. Moreover, the impact of the environment on subjective perception is substantial, as further discussed in Section 4.3 on adaptive theory. The limitations of equivalent temperature indices extend beyond psychological factors. For instance, WBGT adjusts depending on whether direct sunlight is present. Under direct sunlight, the weights are 0.7 for wet-bulb temperature, 0.2 for globe temperature, and 0.1 for dry-bulb temperature. In the absence of direct sunlight, the globe temperature and dry-bulb temperature are considered equal, summing up to the dry-bulb temperature with a weight of 0.3 [13,57]. These coefficients are determined considering both sensible heat (dry-bulb temperature and globe temperature) and latent heat (humidity affecting sweat evaporation reflected in wet-bulb temperature), which collectively influence human heat dissipation and correlate strongly with heat injuries. It is important to note that the fixed coefficients used in WBGT calculations do not account for active physiological regulation by the human body under varying environmental conditions. Therefore, the application of these coefficients should be restricted to environments where sweating occurs due to high temperatures, assuming constant factors like clothing and metabolic rates similar to those in the original data [13,57].

The introduction of thermophysiological regulation models has addressed some of the previously mentioned issues. However, these models still lack flexibility. This is because the heat exchange calculations, whether in equivalent temperature or PMV, are based on the average data of a specific group of people, while the processing of thermal sensation generally employs a group model, completely disregarding individual differences in this thermal comfort assessment. For example, in multi-node models, dimensions and layers of the human body are based on average sizes [18,70]. Additionally, these models rely on empirical mean values from existing studies for physiological responses, including blood flow, heat exchange, sweat rate, and other factors. [18].

3.3. Information loss

In many thermal comfort studies that use equivalent temperature and PMV, there is an implicit assumption that people's thermal perceptions are the same at identical equivalent temperatures. However, no studies have verified the validity of this assumption. Equivalent temperature is developed entirely based on physiological parameters and does not account for any subjective thermal perception information.

Firstly, it is important to discuss that within the calculation logic of indices such as SET and UTCI, the iterative adjustment of the temperature within the reference environment integrates multiple physiological states to form a composite indicator function [58,69]. However, this approach only ensures equivalence of the indicator function between the reference and real environments, without guaranteeing exact equivalence across individual physiological parameters [71]. Taking SET as an example, even if its calculation program is entirely correct, it is unlikely that skin temperature, skin wettedness, and heat exchange in the standard environment will simultaneously match those in the real environment.

Furthermore, even if all physiological parameters are ensured to be identical, we cannot guarantee that two environments will elicit the same subjective sensations among individuals. For instance, increases in temperature, humidity, clothing insulation, metabolic and decreases in air speed may all result in increased equivalent temperatures. However, the impacts of these changes in these six parameters on subjective feelings (such as satisfaction, comfort, pleasure, etc.) are also difficult to equate. Different combinations of environmental parameters yield a single equivalent temperature, and when regressed against Thermal Sensation Votes, each equivalent temperature value corresponds to only one TSV result. This implies that each unique combination of environmental parameters corresponds to a specific thermal sensation. However, ensuring this correspondence is inherently challenging. Furthermore, if thermal sensation, thermal satisfaction, and thermal comfort are further regressed, it is assumed that comfort or satisfaction levels remain consistent across different combinations of environmental parameters. This assumption is even more difficult to uphold. Thus, within the processing logic of ***environmental parameters-equivalent temperature-thermal sensation-thermal comfort***, continuous information loss occurs, resulting in a significant deviation from the actual comfort range.

The excessive simplification of heat exchange and physiological parameter calculations raises concerns about their reliability. Moreover, even if heat balance and physiological parameters are identical, there is no guarantee of consistent subjective perceptions. Therefore, we have reason to believe that in thermal comfort assessments focused on human perception, moving away from heat balance calculations may yield better results.

4. Models

Indicators based on group average responses may provide a simple and effective means for setting standards and conducting basic thermal environment assessments, but they fall far short of meeting the current demands for automated and high-quality environmental control. There are numerous applicable evaluation frameworks available for developing thermal comfort assessment models that are both practical and highly accurate.

4.1. Models based on physiological parameter

Due to the close relationship between human thermophysiological states and thermal sensation, thermophysiological models are not only used for equivalent temperature calculations but also for the development of thermal sensation prediction models.

For instance, alongside the development of thermophysiological models, Fiala introduced the Dynamic Thermal Sensation (DTS) model, which integrates thermophysiological models into a process that links environmental parameter inputs to thermal sensation prediction outputs. DTS utilizes deviations in skin temperature, head core temperature from a reference point, and their temporal changes (for dynamic issues), employing regression fitting to derive 7-point thermal sensation predictions [63]. Similarly, based on the Stolwijk model, Huizenga and Zhang et al. developed a multi-node thermophysiological model [72], calculating local thermal sensation for each body node based on skin temperature, core temperature, and their temporal variations, subsequently developing models for overall thermal sensation and thermal comfort based on the complex relationships between local and overall thermal perception [73–77]. Lai et al. developed a new model based on Fiala's model [78], subsequently establishing a dynamic thermal sensation prediction model for outdoor environments based on average skin temperature, its temporal changes, and human thermal loads [79].

With advancements in physiological monitoring sensors and the need for automated control, models directly monitoring physiological parameters to assess thermal sensation have been developed. These applications partially bypass the cumbersome processes and errors associated with thermophysiological calculations. However, according to Chen et al. [80], who summarized 74 studies on predicting individual thermal comfort based on physiological signals, only 29 studies or fewer involved subjective information beyond thermal sensation.

Among various physiological signals, relative successful models have been established based on the relationship between skin temperature characteristics and thermal sensation [81,82]. While non-contact measurement of physiological features offers new avenues for automated control, current models primarily focus on modeling thermal sensation, with limited research on the models of physiological parameters related to comfort and other emotional responses. Moreover, subjective feedback is still required to establish relationships between physiological parameters and thermal sensation to determine whether detected physiological states indicate cool, warm, or neutral, thereby providing signals for environmental control.

We resummarized the subjective information from a review of 36 articles on personal thermal comfort models using infrared technology [83]. Among them, 14 studies used different scales of TSV to represent thermal comfort, 2 studies involved TPV. 8 studies did not include subjective information, focusing instead on recognizing and extracting information such as clothing insulation, skin temperature, and age, or using this data to replace calculation modules in PMV. Five studies used Bedford-type scales, which combine thermal sensation and thermal comfort. Two studies employed Zhang et al.'s models on skin temperature and perceived comfort. Three studies involved both TSV and TCV, but these were closer to exploratory studies, using variance analysis or regression to identify significant factors affecting TCV, usually with low R^2 values, and their purpose was not to improve model accuracy. Among them, only two studies by Aryal and Becerik-Gerbe [84,85] successfully developed models for thermal sensation and thermal satisfaction, and these feedbacks were actually used for environmental control.

Besides skin temperature, other physiological parameters considered highly relevant to human thermal perception within thermophysiological models include core temperature, sweating rate, and skin wettedness. However, due to measurement difficulties and accuracy limitations, these parameters are less mature for thermal sensation prediction compared to skin temperature. Beyond thermophysiological parameters, studies in thermal comfort have also explored variables such as heart rate variability [86,87], skin conductance, electroencephalography (EEG), and blood oxygen saturation [88] yet the performance of related models remains to be evaluated due to measurement challenges and predictive limitations. Although skin temperature is a highly useful predictor of thermal sensation and can detect localized discomfort, its response to air movement and humidity may be limited. Integrating environmental parameters and various physiological signals could provide an effective solution for real-time assessment of individual comfort.

4.2. Behavioral models

In the context of comfort assessment, occupant behavior holds significant potential. Unlike the logic underlying the establishment of all aforementioned models, behavioral learning theoretically may not necessitate subjective voting to gauge human perception. The logic here is that environmental stimuli generate perceptions, and deviations from comfort points lead to discomfort. Driven by these perceptions, individuals exhibit adjustment behaviors to achieve comfort [89]. Therefore, by learning patterns of how people adjust their behaviors in relation to their environment, it is theoretically possible to ascertain individuals' genuine preferences and habits regarding thermal environments. Behaviors directly related to thermal environments and thermal comfort are primarily focused on studies of thermostat set points. For example, in their study of energy flexibility, Kaspar et al. used K-means clustering to categorize two groups of households based on indoor temperature setpoints, and they measured comfort using the total number of unmet setpoint hours and the number of thermostat overrides [90]. Similarly, Huchuk et al. analyzed thermostat usage data from North America and found that users' thermal preferences showed seasonal variations, which generally aligned with existing models of thermal preferences [91]. Both studies used data from the "Donate Your Data" dataset provided by thermostat manufacturer ecobee Inc. Several other studies have referenced this dataset [92,93], applying different analytical methods to explore people's preferred setpoints and the impact of factors such as climate zone and time on these preferences. Lyu et al., using residential air conditioning temperature setpoint behaviors provided by Midea Air-Conditioning Equipment Co., Ltd., calculated the setpoints people chose at different times and developed a model of user preferences [94]. These studies on smart air conditioner setpoints clearly demonstrate the feasibility and reliability of conducting thermal comfort research without relying on questionnaires, though securing large-scale, high-quality data sources is essential.

Another well-researched area focuses on behavior related to occupant schedules [95,96]. Occupant presence is crucial for both energy savings and maintaining comfort in buildings, especially in the context of automatically controlled HVAC systems to ensure thermal comfort, though this research does not directly assess comfort. Other behavioral studies, such as window opening and closing [97], curtain adjustment [98,99], fan operation [100,101], and clothing habits [102], are also related to maintaining thermal comfort, though their primary focus is not on deriving information about comfort temperatures or preferences from behavior. Behavioral research is also included in some specialized research concepts, such as Occupant-centric control and Human-building interaction [103], and in international cooperative efforts like IEA-EBC Annex 66: Definition and Simulation of Occupant Behavior in Buildings [104] and IEA-EBC Annex 79: Occupant-Centric Building Design and Operation [105].

Although behavioral research holds valuable potential in thermal comfort studies, it faces challenges beyond data availability, such as requiring investigations in real-world environments where occupants have full control over their surroundings. Quantifying behavior is also challenging, especially when driven by multi-domain factors [106]. For example, window-opening behavior may be influenced by a combination of thermal conditions, noise, and air quality. Additionally, in a time-series context, different behavioral actions can lead to subsequent changes in the thermal environment, further complicating the relationship between actions and perceptions. Unified analysis of time duration and granularity may yield valuable research results for this direction and intelligent control systems.

4.3. Adaptive theory

The development of the aforementioned models originally aimed to create universal models applicable across various scenarios, thereby often overlooking the influences of context information such as climate zone, building type, ventilation patterns [107], and individual differences including height, weight, body fat percentage, age, gender, and race [108]. The "one size fits all" environmental design according to classical thermal comfort models has not consistently achieved desired satisfaction rates, prompting the evolution of adaptive theory and personalized models.

Nicol and Humphreys first proposed adaptive theory in 1973 [89], followed by quantified results provided by de Dear and Brager in 1998 [31]. "The adaptive approach to modeling thermal comfort acknowledges that thermal perception in 'real world' settings is influenced by the complexities of past thermal history and cultural and technical practices [40]." EN-16798 [109] gives the expression as "Physiological, psychological or behavioral adjustment of building occupants to the interior thermal environment in order to avoid or to limit thermal discomfort. In naturally ventilated buildings these are often in response to changes in indoor environment induced by outside weather conditions." ASHRAE-55 [5] gives the expression as "A model that relates indoor design temperatures or acceptable temperature ranges outdoor meteorological or climatological parameters".

Adaptive theory also emphasizes the importance of context, which not only influences people's activities but also shapes their perception of the environment, their tolerance, and their expectations. Specifically, when considering how individuals can reduce thermal discomfort through interactions with the environment, adjusting clothing, activities, etc. [110], as well as adapting to climatic conditions and psychological expectations for different building environments [107,111], the comfortable temperatures people exhibit are correlated with outdoor temperatures [31].

However, this correlation is a result of adaptive behavior rather than its root cause. A range of broader factors, such as the building type, its intended use, orientation, level of sun shading, and whether occupants can open windows, significantly influence thermal perception. These elements shape how individuals perceive their environment and impact their tolerance [40,112–115]. This underscores a key limitation of indices and models that focus solely on internal physiology and immediate thermal surroundings, neglecting the broader context. Considering the influence of climate, building design, and HVAC system variations on physiological and psychological adaptation, many studies have built new indices based on the PMV model [110,116,117]. However, as they do not alter the core logic of traditional models, their overall impact on accuracy improvement is limited [56].

Although adaptive theory is primarily used in current standards to address thermal comfort in naturally ventilated or mixed-mode buildings, occupants in air-conditioned buildings also demonstrate adaptive behaviors. Maintaining a neutral temperature in air-conditioned environments may neither improve comfort nor conserve energy. Thoughtfully designed applications of adaptive theory to air-conditioning control could result in significant energy savings, especially when combined with Personalized Environmental Control Systems, which would further ensure occupant comfort.

4.4. Personal thermal comfort model

Apart from the background information mentioned above, the impact of individual differences is also significant [118]. Variables such as sex[23,118–120], age[121–124], race[70,108,125], BMI as well as various physiological, psychological, and other factors, can cause individuals in the same environment to experience different thermal sensations [62]. It is impractical to rely on a single model to create one environment that meets everyone's needs. To address this issue, Personal Thermal Comfort Models have been developed.

The framework for establishing personal comfort models includes the collection of raw data (encompassing environmental, physiological, and subjective data) as well as the modeling process. Unlike general population comfort models, Personal Thermal Comfort Models are typically developed through long-term and extensive data collection from specific individuals. Most studies incorporate personal characteristics as inputs, such as sex, age, and other factors, to enhance the model's generalizability. The effects of these individual differences on thermophysiology are also captured through physiological sensing technologies, making many personal thermal comfort models closely linked with physiological monitoring research. The combination of infrared imaging and personal thermal comfort systems has been a frequent topic of study [83]. For example, Rida et al. developed a model using computer vision to extract key features related to thermal comfort, such as activity level, clothing insulation, posture, age, and sex, from an RGB image sequence, while extracting limited skin temperatures from infrared images.

We continue to focus on the subjective information aspect of personal thermal comfort systems. In the systematic review by Martins et al. [126] on personal thermal comfort models, they summarized the output categories and scales of various models. Among the 37 studies listed, 30 used only thermal sensation, thermal preference, or a combination of both, with 18 studies focusing solely on thermal sensation. Additionally, most research has been conducted in a single context or season, such as in air-conditioned offices during cooling seasons. This limitation means that the models only recognize an individual's preferred temperature within specific times and seasons.

5. Future work

5.1. Research frameworks

This paper primarily focuses on the subjective information involved in various levels of thermal comfort evaluation methods, with thermal sensation being the most commonly used representative indicator, especially in practical applications. In the future, thermal environment assessments should avoid over-reliance on thermal sensation and instead treat it as just one aspect of thermal comfort evaluation. For instance, a research framework overly dependent on thermal sensation may resemble Framework 1 in Fig. 3, where equivalent temperature or the PMV index aggregates various factors into a single thermal sensation value, which is then used to infer comfort levels. This process overlooks a wealth of information. In contrast, a research framework that treats thermal sensation as one component of thermal comfort should resemble Framework 2. In this framework, the first step is to determine whether the environment is comfortable. If it is, the environmental characteristics are summarized. If it is uncomfortable, the next step is to assess whether the thermal sensation is neutral. If it is not neutral, the non-neutral condition might be the source of discomfort. However, if it is neutral, this can help identify other possible causes of thermal discomfort. Of course, in real-world environments, considering not only thermal factors but also multiple domains would contribute to an overall improvement in the environment.

5.2. Subjective prediction models and data-driven approaches

Due to the complexity of subjective emotions and the numerous influencing factors, various machine learning algorithms provide effective pathways for accurately predicting different aspects of thermal comfort. Whether developing thermal comfort prediction models or implementing human-in-the-loop HVAC control, it is recommended to evaluate thermal environments using multiple dimensions such as thermal sensation and comfort. For instance, in smart control applications that aim to save energy by introducing fans, both thermal sensation and potential sources of discomfort, such as draft sensation, should be considered.

Given the "black box" nature of models, it is suggested that future model development should include detailed descriptions or open access to the data characteristics used for development, allowing for further research on model generalization. Additionally, when data-driven models can incorporate more diverse and broadly representative data, they are likely to achieve a wider applicability. With the advancements in big data computing and storage capabilities, it is now feasible to establish global database resources. To compare the accuracy of different black box models, establishing a database that covers various predictor and response variables for model comparison could facilitate both cross-sectional comparisons and longitudinal improvement of different models.

5.3. Application of thermal comfort indices to specific scenarios

Users have varying thermal comfort requirements depending on the specific scenario: work environments demand thermal conditions that keep users alert, focused, and efficient; residential environments require conditions that make occupants feel relaxed and content; sleep environments need conditions that enhance sleep quality; semi-outdoor shopping spaces aim to increase foot traffic and sales; and pocket parks require conditions that mitigate urban heat island effects and provide comfortable resting areas for nearby residents. Thermal comfort indices should be established with consideration of these specific service needs, avoiding a "one index for all, thermal neutral for all" approach. A large amount of existing climate chamber data aims to explore the clear relationship between thermal environment parameters, thermal physiology, and thermal perception by avoiding the introduction of lifestyle

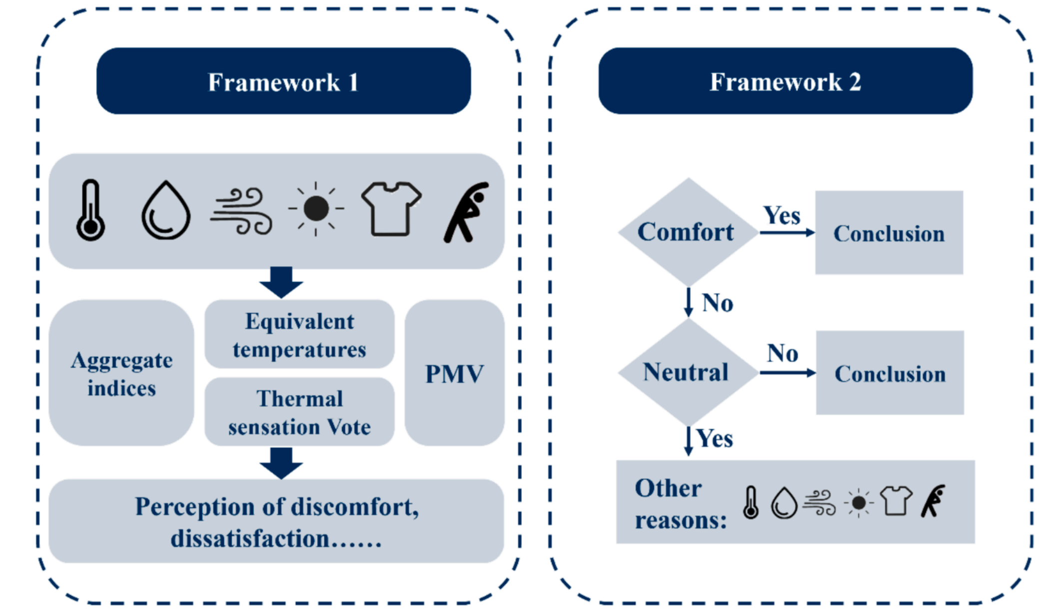

Fig. 3. Two types of research frameworks for thermal comfort.

factors during experimental setups. Test subjects, when evaluating thermal environments, focus solely on this task, leading to discrepancies when these thermal perception models are applied in real-world scenarios. Therefore, when evaluating thermal comfort in real-world scenarios, the influence of contextual effects on subjective perception should be considered. Additionally, the objectives of real-world scenarios should incorporate indicators beyond thermal comfort, such as using productivity to assess thermal environments in work settings.

6. Conclusion

(1) Subjective thermal perception is foundational to thermal environment assessment. However, current indices, models, and guidelines often overlook the multidimensionality of thermal perception, leading to an overreliance on thermal sensation and thermal neutrality.
(2) Classical equivalent temperature indices do not incorporate subjective comfort information at all, and PMV primarily relies on heat exchange to assess thermal sensation. With advancements in data processing capabilities and the understanding that thermal perception is influenced by multiple factors beyond heat exchange and thermophysiology, directly establishing relationships between various influencing factors and thermal comfort may provide a more effective approach to evaluating the comfort of thermal environments compared to traditional heat exchange-based indices.
(3) Most physiologically-driven or personal models still primarily focus on predicting thermal sensation votes, neglecting other useful subjective information. Additionally, there is significant variability in voting scales, and a lack of data resources and standards for cross-comparison. Behavioral research in real-world environments has the potential to replace subjective questionnaires in the study of thermal comfort preferences.
(4) Subjective thermal comfort assessment should fully consider adaptive theory and individual differences. Adaptive models clearly demonstrate that a "one size fits all" approach to environmental design limits the improvement of environmental satisfaction. Advances in technology provide favorable conditions for the development of personalized thermal comfort models, which could be an effective way to further improve thermal environment quality.

CRediT authorship contribution statement

Yuxin Yang: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Junmeng Lyu:** Writing – review & editing, Writing – original draft, Visualization. **Zhiwei Lian:** Writing – review & editing, Supervision, Resources, Conceptualization. **Yongxin Xie:** Writing – review & editing, Writing – original draft, Visualization. **Ying Jiang:** Writing – review & editing, Writing – original draft. **Junwei Lin:** Writing – review & editing, Writing – original draft. **Jianlei Niu:** Writing – review & editing, Supervision, Resources.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

References

[1] R. de Dear, Thermal comfort in practice, Indoor Air 14 (2004) 32–39, https://doi.org/10.1111/j.1600-0668.2004.00270.x.
[2] Z. Lian, Revisiting thermal comfort and thermal sensation, Build. Simul. 17 (2024), https://doi.org/10.1007/s12273-024-1107-8.
[3] S. Liu, N. Nazarian, J. Niu, M.A. Hart, R. de Dear, From thermal sensation to thermal affect: A multi-dimensional semantic space to assess outdoor thermal comfort, Build. Environ. 182 (2020) 107112, https://doi.org/10.1016/j.buildenv.2020.107112.
[4] Z. Wang, J. Wang, Y. He, Y. Liu, B. Lin, T. Hong, Dimension analysis of subjective thermal comfort metrics based on ASHRAE Global Thermal Comfort Database using machine learning, Journal of Building Engineering 29 (2020) 101120, https://doi.org/10.1016/j.jobe.2019.101120.
[5] ASHRAE. ANSI/ASHRAE Standard 55-2023, Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 2023.
[6] K. Parsons Human Thermal Environments: The Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort, and Performance, Third Edition 3rd ed., 2014 CRC Press Boca Raton 10.1201/b16750.

[7] F.C. Houghten, C.P. Yaglou, Determining lines of equal comfort, Journal of the American Society of Heating and Ventilation in England 29 (1923) 165–176.
[8] A.P. Gagge, Chapter 5 Rational Temperature Indices of Thermal Comfort, in: Studies in Environmental Science, Elsevier, 1981: pp. 79–98. 10.1016/S0166-1116(08)71082-3.
[9] A.P. Gagge, J.A.J. Stolwijk, B. Saltin, Comfort and thermal sensations and associated physiological responses during exercise at various ambient temperatures, Environ. Res. 2 (1969) 209–229, https://doi.org/10.1016/0013-9351(69)90037-1.
[10] Y. Epstein, D.S. Moran, Thermal Comfort and the Heat Stress Indices, Ind. Health 44 (2006) 388–398, https://doi.org/10.2486/indhealth.44.388.
[11] C.R. de Freitas, E.A. Grigorieva, A comparison and appraisal of a comprehensive range of human thermal climate indices, Int. J. Biometeorol. 61 (2017) 487–512, https://doi.org/10.1007/s00484-016-1228-6.
[12] O. Potchter, P. Cohen, T.-P. Lin, A. Matzarakis, Outdoor human thermal perception in various climates: A comprehensive review of approaches, methods and quantification, Sci. Total Environ. 631–632 (2018) 390–406, https://doi.org/10.1016/j.scitotenv.2018.02.276.
[13] C.P. Yaglou, D. Minard, Control of heat casualties at military training centers, A.M.A. Arch. Ind. Health 16 (1957) 302–316.
[14] Y. (Don) Guan, M.H. Hosni, B.W. Jones, T.P. Gielda, Literature Review of the Advances in Thermal Comfort Modeling, ASHRAE Trans. 109 (2003) 908–916.
[15] Y. Cheng, J. Niu, N. Gao, Thermal comfort models: A review and numerical investigation, Build. Environ. 47 (2012) 13–22, https://doi.org/10.1016/j.buildenv.2011.05.011.
[16] J.A.J. Stolwijk, A mathematical model of physiological temperature regulation in man (1971). https://ntrs.nasa.gov/citations/19710023925.
[17] A.P. Gagge, J.A.J. Stolwijk, Y. Nishi, An effective temperature scale based on a simple model of human physiological regulatory response, ASHRAE Trans. 77 (1971) 21–36. http://eprints.lib.hokudai.ac.jp/dspace/bitstream/2115/37901/1/1.
[18] D. Fiala, K.J. Lomas, M. Stohrer, A computer model of human thermoregulation for a wide range of environmental conditions: the passive system, J. Appl. Physiol. 87 (1999) 1957–1972, https://doi.org/10.1152/jappl.1999.87.5.1957.
[19] D. Fiala, G. Havenith, P. Bröde, B. Kampmann, G. Jendritzky, UTCI-Fiala multi-node model of human heat transfer and temperature regulation, Int. J. Biometeorol. 56 (2012) 429–441, https://doi.org/10.1007/s00484-011-0424-7.
[20] P. Drucker, The Practice of Management, Routledge, London (2007), https://doi.org/10.4324/9780080942360.
[21] J. Li, R. Sun, L. Chen, A review of thermal perception and adaptation strategies across global climate zones, Urban Clim. 49 (2023) 101559, https://doi.org/10.1016/j.uclim.2023.101559.
[22] S.K. Sansaniwal, P. Tewari, S. Kumar, S. Mathur, J. Mathur, Impact assessment of air velocity on thermal comfort in composite climate of India, Sci. Technol. Built Environ. 26 (2020) 1301–1320, https://doi.org/10.1080/23744731.2020.1793640.
[23] H. Du, Z. Zhao, J. Lyu, J. Li, Z. liu, X. Li, Y. Yang, L. Lan, Z. Lian, Gender differences in thermal comfort under coupled environmental factors, Energy and Buildings 295 (2023) 113345, https://doi.org/10.1016/j.enbuild.2023.113345.
[24] B. Li, C. Du, M. Tan, H. Liu, E. Essah, R. Yao, A modified method of evaluating the impact of air humidity on human acceptable air temperatures in hot-humid environments, Energ. Buildings 158 (2018) 393–405, https://doi.org/10.1016/j.enbuild.2017.09.062.
[25] C. Buonocore, R. De Vecchi, V. Scalco, R. Lamberts, Influence of relative air humidity and movement on human thermal perception in classrooms in a hot and humid climate, Build. Environ. 146 (2018) 98–106, https://doi.org/10.1016/j.buildenv.2018.09.036.
[26] J.F. Nicol, S. Roaf, Rethinking thermal comfort, Build. Res. Inf. 45 (2017) 711–716, https://doi.org/10.1080/09613218.2017.1301698.
[27] L. Yang, S. Zhao, Y. Zhai, S. Gao, F. Wang, Z. Lian, L. Duanmu, Y. Zhang, X. Zhou, B. Cao, Z. Wang, H. Yan, H. Zhang, E. Arens, R. de Dear, The Chinese thermal comfort dataset, Sci. Data 10 (2023) 662, https://doi.org/10.1038/s41597-023-02568-3.
[28] T. Parkinson, F. Tartarini, V. Földváry Ličina, T. Cheung, H. Zhang, R. De Dear, P. Li, E. Arens, C. Chun, S. Schiavon, M. Luo, G. Brager, ASHRAE global database of thermal comfort field measurements, (2018) 4167577 bytes. 10.6078/D1F671.
[29] T. Parkinson, R. de Dear, Thermal pleasure in built environments: spatial alliesthesia from air movement, Build. Res. Inf. 45 (2017) 320–335, https://doi.org/10.1080/09613218.2016.1140932.
[30] M.A. Humphreys, M. Hancock, Do people like to feel 'neutral'? Energ. Buildings 39 (2007) 867–874, https://doi.org/10.1016/j.enbuild.2007.02.014.
[31] R. de Dear, G.S. Brager, Developing an adaptive model of thermal comfort and preference, Center for the Built Environment, UC Berkeley, 1998 https://escholarship.org/uc/item/4qq2p9c6.
[32] D. Albadra, M. Vellei, D. Coley, J. Hart, Thermal comfort in desert refugee camps: An interdisciplinary approach, Build. Environ. 124 (2017) 460–477, https://doi.org/10.1016/j.buildenv.2017.08.016.
[33] Y. Yang, J. Lyu, H. Du, Z. Lian, W. Liu, L. Duanmu, Y. Zhai, B. Cao, Y. Zhang, X. Zhou, Z. Wang, X. Zhang, F. Wang, Main effects and interactions of multiple key factors related to thermal perception, Sci. Total Environ. 918 (2024) 170683, https://doi.org/10.1016/j.scitotenv.2024.170683.
[34] Z. Xie, B. Cao, Y. Zhu, A novel wind comfort evaluation method for different airflows by considering dynamic characteristics of wind direction and velocity, Build. Environ. 246 (2023) 110976, https://doi.org/10.1016/j.buildenv.2023.110976.
[35] M. Matusiak, Thermal comfort index as a method of assessing the thermal comfort of textile materials, Fibres Text. East. Eur 18 (2010) 79.
[36] A.K. Roy Choudhury, P.K. Majumdar, C. Datta, 1 - Factors affecting comfort: human physiology and the role of clothing, in: G. Song (Ed.), Improving Comfort in Clothing, Woodhead Publishing, 2011: pp. 3–60. 10.1533/9780857090645.1.3.
[37] R. Hu, J. Liu, Y. Xie, J. Jiao, Z. Fang, B. Lin, Effects of mask wearing duration and relative humidity on thermal perception in the summer outdoor built environment, Build. Simul. 16 (2023) 1601–1616, https://doi.org/10.1007/s12273-022-0978-9.
[38] D. Kong, H. Liu, Y. Wu, B. Li, S. Wei, M. Yuan, Effects of indoor humidity on building occupants' thermal comfort and evidence in terms of climate adaptation, Build. Environ. 155 (2019) 298–307, https://doi.org/10.1016/j.buildenv.2019.02.039.
[39] H. Liu, Y. Wu, B. Li, Y. Cheng, R. Yao, Seasonal variation of thermal sensations in residential buildings in the Hot Summer and Cold Winter zone of China, Energ. Buildings 140 (2017) 9–18, https://doi.org/10.1016/j.enbuild.2017.01.066.
[40] G.S. Brager, R. de Dear, Thermal adaptation in the built environment: a literature review, Energ. Buildings 27 (1998) 83–96, https://doi.org/10.1016/S0378-7788(97)00053-4.
[41] ISO 7730, Ergonomics of the thermal Environment-analytical Determination and Interpretation of thermal comfort Using Calculation of the PMV and PPD Indices and Local thermal comfort Criteria, (2005). https://www.iso.org/standard/39155.html (accessed December 23, 2022).
[42] S. Liu, Y. Xie, Y. Zhu, B. Lin, B. Cao, N.H. Wong, J. Niu, Z. Fang, D. Lai, W. Liu, J. Wen, D. Mou, H. Tang, Z. Liu, M. Ignatius, Comparative analysis on indoor and outdoor thermal comfort in transitional seasons and summer based on multiple databases: Lessons learnt from the outdoors, Sci. Total Environ. 848 (2022) 157694, https://doi.org/10.1016/j.scitotenv.2022.157694.
[43] Y. Xie, T. Huang, J. Li, J. Liu, J. Niu, C.M. Mak, Z. Lin, Evaluation of a multi-nodal thermal regulation model for assessment of outdoor thermal comfort: Sensitivity to wind speed and solar radiation, Build. Environ. 132 (2018) 45–56, https://doi.org/10.1016/j.buildenv.2018.01.025.
[44] J. Spagnolo, R. de Dear, A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia, Build. Environ. 38 (2003) 721–738, https://doi.org/10.1016/S0360-1323(02)00209-3.
[45] K. Liu, Z. Lian, X. Dai, D. Lai, Comparing the effects of sun and wind on outdoor thermal comfort: A case study based on longitudinal subject tests in cold climate region, Sci. Total Environ. 825 (2022) 154009, https://doi.org/10.1016/j.scitotenv.2022.154009.
[46] J. Li, J. Wang, J. Niu, Elderly residents' uses of fragmented outdoor spaces in public housing estates in Hong Kong——Decoding causality and heat-risk exposure, Build. Environ. 245 (2023) 110912, https://doi.org/10.1016/j.buildenv.2023.110912.
[47] M.R. Hunter, B.W. Gillespie, S.-Y.-P. Chen, Urban Nature Experiences Reduce Stress in the Context of Daily Life Based on Salivary Biomarkers, Front. Psychol. 10 (2019) 722, https://doi.org/10.3389/fpsyg.2019.00722.
[48] D. Lai, Z. Lian, W. Liu, C. Guo, W. Liu, K. Liu, Q. Chen, A comprehensive review of thermal comfort studies in urban open spaces, Sci. Total Environ. 742 (2020) 140092, https://doi.org/10.1016/j.scitotenv.2020.140092.
[49] S. Liu, B. Cao, Y. Zhu, Experimental study on comparison of indoor and multiple outdoor thermal environments excluding visual and acoustic interference, Sustain. Cities Soc. 94 (2023) 104564, https://doi.org/10.1016/j.scs.2023.104564.
[50] M. Schweiker, X. Fuchs, S. Becker, M. Shukuya, M. Dovjak, M. Hawighorst, J. Kolarik, Challenging the assumptions for thermal sensation scales, Build. Res. Inf. 45 (2017) 572–589, https://doi.org/10.1080/09613218.2016.1183185.
[51] J. Kim, J. Ryu, B. Jeong, R. de Dear, Semantic discrepancies between Korean and English versions of the ASHRAE sensation scale, Build. Environ. 221 (2022) 109343, https://doi.org/10.1016/j.buildenv.2022.109343.
[52] J.-Y. Lee, Y. Tochihara, H. Wakabayashi, E.A. Stone, Warm or Slightly Hot? Differences in Linguistic Dimensions Describing Perceived Thermal Sensation, J. Physiol. Anthropol. 28 (2009) 37–41, https://doi.org/10.2114/jpa2.28.37.
[53] H. Al-Khatri, M.B. Gadi, Investigating the behaviour of ASHRAE, Bedford, and Nicol thermal scales when translated into the Arabic language, Build. Environ. 151 (2019) 348–355, https://doi.org/10.1016/j.buildenv.2019.01.051.
[54] M. Schweiker, A. Abdul-Zahra, M. André, F. Al-Atrash, H. Al-Khatri, R. R. Alprianti, H. Alsaad, R. Amin, E. Ampatzi, A.Y. Arsano, M. Azadeh, E. Azar, B. Bahareh, A. Batagarawa, S. Becker, C. Buonocore, B. Cao, J.-H. Choi, C. Chun, H. Daanen, S.A. Damiati, L. Daniel, R.D. Vecchi, S. Dhaka, S. Domínguez-Amarillo, E. Dudkiewicz, L.P. Edappilly, J. Fernández-Agüera, M. Folkerts, A. Frijns, G. Gaona, V. Garg, S. Gauthier, S.G. Jabbari, D. Harimi, R.T. Hellwig, G. M. Huebner, Q. Jin, M. Jowkar, R. Kania, J. Kim, N. King, B. Kingma, M. D. Koerniawan, J. Kolarik, S. Kumar, A. Kwok, R. Lamberts, M. Laska, M.C.J. Lee, Y. Lee, V. Lindermayr, M. Mahaki, U. Marcel-Okafor, L. Marín-Restrepo, A. Marquardsen, F. Martellotta, J. Mathur, G. McGill, I. Mino-Rodriguez, D. Mou, B. Moujalled, M. Nakajima, E. Ng, M. Okafor, M. Olweny, W. Ouyang, A.L. Papst de Abreu, A. Pérez-Fargallo, I. Rajapaksha, G. Ramos, S. Rashid, C.F. Reinhart, M. I. Rivera, M. Salmanzadeh, K. Schakib-Ekbatan, S. Schiavon, S. Shooshtarian, M. Shukuya, V. Soebarto, M. Suhendri, F. Tahsildoost, D. Tartarini, P. Teli, S. Tewari, M. Thapa, J. Trebilcock, R.B. Trojan, C. Tukur, Y. Voelker, L. Yam, G. Yang, Y. Zapata-Lancaster, Y. Zhai, Z.S.Z. Zhu, The Scales Project, a cross-national dataset on the interpretation of thermal perception scales, Sci Data 6 (2019) 289, https://doi.org/10.1038/s41597-019-0272-6.

[55] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II, Build. Environ. 153 (2019) 205–217, https://doi.org/10.1016/j.buildenv.2019.01.055.
[56] H. Du, Z. Lian, D. Lai, L. Duanmu, Y. Zhai, B. Cao, Y. Zhang, X. Zhou, Z. Wang, X. Zhang, Z. Hou, Evaluation of the accuracy of PMV and its several revised models using the Chinese thermal comfort Database, Energ. Buildings 271 (2022) 112334, https://doi.org/10.1016/j.enbuild.2022.112334.
[57] G.M. Budd, Wet-bulb globe temperature (WBGT)—its history and its limitations, J. Sci. Med. Sport 11 (2008) 20–32, https://doi.org/10.1016/j.jsams.2007.07.003.
[58] A.P. Gagge, Y. Nishi, R.R. Gonzalez, Standard effective temperature - A single temperature index of temperature sensation and thermal discomfort, in: Symposium on Thermal Comfort and Moderate Heat Stress, CIB Commission W45 (Human Requirements), Building Research Establishment, London, 1972: pp. 229–250. http://www.researchgate.net/publication/284756199_Standard_effective_temperature_-_A_single_temperature_index_of_temperature_sensation_and_thermal_discomfort.
[59] G. Jendritzky, R. De Dear, G. Havenith, UTCI—Why another thermal index? Int. J. Biometeorol. 56 (2012) 421–428, https://doi.org/10.1007/s00484-011-0513-7.
[60] K. Błażejczyk, G. Jendritzky, P. Bröde, D. Fiala, G. Havenith, Y. Epstein, A. Psikuta, B. Kampmann, An introduction to the Universal Thermal Climate Index (UTCI), Geogr. Pol. 86 (2013) 5–10, https://doi.org/10.7163/GPol.2013.1.
[61] P. Höppe, The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment, Int. J. Biometeorol. 43 (1999) 71–75, https://doi.org/10.1007/s004840050118.
[62] P.O. Fanger, Thermal comfort. Analysis and applications in environmental engineering, Danish Technical Press, Copenhagen, 1970.
[63] D. Fiala, K.J. Lomas, M. Stohrer, First principles modeling of thermal sensation responses in steady-state and transient conditions, ASHRAE Trans. 109 (2003) 179.
[64] D. Enescu, A review of thermal comfort models and indicators for indoor environments, Renew. Sustain. Energy Rev. 79 (2017) 1353–1379, https://doi.org/10.1016/j.rser.2017.05.175.
[65] R.J. de Dear, Global database of thermal comfort field experiments, In (1998) 1141–1152.
[66] A.P. Gagge, A.P. Fobelets, L.G. Berglund, A standard predictive index of human response to the thermal environment, ASHRAE Trans. 92 (1986).
[67] G.R. McGregor, Special issue: Universal Thermal Comfort Index (UTCI), Int. J. Biometeorol. 56 (2012) 419, https://doi.org/10.1007/s00484-012-0546-6.
[68] G. Havenith, D. Fiala, K. Błazejczyk, M. Richards, P. Bröde, I. Holmér, H. Rintamaki, Y. Benshabat, G. Jendritzky, The UTCI-clothing model, Int. J. Biometeorol. 56 (2012) 461–470, https://doi.org/10.1007/s00484-011-0451-4.
[69] P. Bröde, D. Fiala, K. Błażejczyk, I. Holmér, G. Jendritzky, B. Kampmann, B. Tinz, G. Havenith, Deriving the operational procedure for the Universal Thermal Climate Index (UTCI), Int. J. Biometeorol. 56 (2012) 481–494, https://doi.org/10.1007/s00484-011-0454-1.
[70] X. Zhou, H. Zhang, Z. Lian, Y. Zhang, A model for predicting thermal sensation of Chinese people, Build. Environ. 82 (2014) 237–246, https://doi.org/10.1016/j.buildenv.2014.08.006.
[71] H. Du, C. Yang, Re-visitation of the thermal environment evaluation index standard effective temperature (SET*) based on the two-node model, Sustain. Cities Soc. 53 (2020) 101899, https://doi.org/10.1016/j.scs.2019.101899.
[72] C. Huizenga, Z. Hui, E. Arens, A model of human physiology and comfort for assessing complex thermal environments, Build. Environ. 36 (2001) 691–699, https://doi.org/10.1016/S0360-1323(00)00061-5.
[73] H. Zhang, Human thermal sensation and comfort in transient and non-uniform thermal environments, Center for the Built Environment, UC Berkeley, 2003 https://escholarship.org/uc/item/11m0n1wt.
[74] H. Zhang, E. Arens, C. Huizenga, T. Han, Thermal sensation and comfort models for non-uniform and transient environments: Part I: Local sensation of individual body parts, Build. Environ. 45 (2010) 380–388, https://doi.org/10.1016/j.buildenv.2009.06.018.
[75] H. Zhang, E. Arens, C. Huizenga, T. Han, Thermal sensation and comfort models for non-uniform and transient environments, part II: Local comfort of individual body parts, Build. Environ. 45 (2010) 389–398, https://doi.org/10.1016/j.buildenv.2009.06.015.
[76] H. Zhang, E. Arens, C. Huizenga, T. Han, Thermal sensation and comfort models for non-uniform and transient environments, part III: Whole-body sensation and comfort, Build. Environ. 45 (2010) 399–410, https://doi.org/10.1016/j.buildenv.2009.06.020.
[77] Y. Zhao, H. Zhang, E.A. Arens, Q. Zhao, Thermal sensation and comfort models for non-uniform and transient environments, part IV: Adaptive neutral setpoints and smoothed whole-body sensation model, Build. Environ. 72 (2014) 300–308, https://doi.org/10.1016/j.buildenv.2013.11.004.
[78] D. Lai, Q. Chen, A two-dimensional model for calculating heat transfer in the human body in a transient and non-uniform thermal environment, Energ. Buildings 118 (2016) 114–122, https://doi.org/10.1016/j.enbuild.2016.02.051.
[79] D. Lai, X. Zhou, Q. Chen, Modelling dynamic thermal sensation of human subjects in outdoor environments, Energ. Buildings 149 (2017) 16–25, https://doi.org/10.1016/j.enbuild.2017.05.028.
[80] K. Chen, Q. Xu, B. Leow, A. Ghahramani, Personal thermal comfort models based on physiological measurements – A design of experiments based review, Build. Environ. 228 (2023) 109919, https://doi.org/10.1016/j.buildenv.2022.109919.
[81] Z. Wang, R. Matsuhashi, H. Onodera, Intrusive and non-intrusive early warning systems for thermal discomfort by analysis of body surface temperature, Appl. Energy 329 (2023) 120283, https://doi.org/10.1016/j.apenergy.2022.120283.
[82] J. Lyu, H. Du, Z. Zhao, Y. Shi, B. Wang, Z. Lian, Where should the thermal image sensor of a smart A/C look?-Occupant thermal sensation model based on thermal imaging data, Build. Environ. 239 (2023) 110405, https://doi.org/10.1016/j.buildenv.2023.110405.
[83] Y. Wu, J. Zhao, B. Cao, A systematic review of research on personal thermal comfort using infrared technology, Energ. Buildings 301 (2023) 113666, https://doi.org/10.1016/j.enbuild.2023.113666.
[84] A. Aryal, B. Becerik-Gerber, A comparative study of predicting individual thermal sensation and satisfaction using wrist-worn temperature sensor, thermal camera and ambient temperature sensor, Build. Environ. 160 (2019) 106223, https://doi.org/10.1016/j.buildenv.2019.106223.
[85] A. Aryal, B. Becerik-Gerber, Thermal comfort modeling when personalized comfort systems are in use: Comparison of sensing and learning methods, Build. Environ. 185 (2020) 107316, https://doi.org/10.1016/j.buildenv.2020.107316.
[86] Z. Wang, R. Matsuhashi, H. Onodera, Towards wearable thermal comfort assessment framework by analysis of heart rate variability, Build. Environ. 223 (2022) 109504, https://doi.org/10.1016/j.buildenv.2022.109504.
[87] W. Liu, Z. Lian, Y. Liu, Heart rate variability at different thermal comfort levels, Eur. J. Appl. Physiol. 103 (2008) 361–366, https://doi.org/10.1007/s00421-008-0718-6.
[88] T. Chaudhuri, Y.C. Soh, H. Li, L. Xie, Machine learning driven personal comfort prediction by wearable sensing of pulse rate and skin temperature, Build. Environ. 170 (2020) 106615, https://doi.org/10.1016/j.buildenv.2019.106615.
[89] F. Nicol, M. Humphreys, Thermal comfort as part of a self-regulating system, Build. Res. Inf. 1 (1973) 174–179, https://doi.org/10.1080/09613217308550237.
[90] K. Kaspar, K. Nweye, G. Buscemi, A. Capozzoli, Z. Nagy, G. Pinto, U. Eicker, M. M. Ouf, Effects of occupant thermostat preferences and override behavior on residential demand response in CityLearn, Energ. Buildings 324 (2024) 114830, https://doi.org/10.1016/j.enbuild.2024.114830.
[91] B. Huchuk, W. O'Brien, S. Sanner, A longitudinal study of thermostat behaviors based on climate, seasonal, and energy price considerations using connected thermostat data, Build. Environ. 139 (2018) 199–210, https://doi.org/10.1016/j.buildenv.2018.05.003.
[92] K. Panchabikesan, M. Ouf, U. Eicker, G. Newsham, H. Knudsen, Investigating thermostat setpoint preferences in Canadian households, in: 2021. 10.26868/25222708.2021.30433.
[93] L. Sarran, H.B. Gunay, W. O'Brien, C.A. Hviid, C. Rode, A data-driven study of thermostat overrides during demand response events, Energy Policy 153 (2021) 112290, https://doi.org/10.1016/j.enpol.2021.112290.
[94] J. Lyu, J. Li, Z. Zhao, X. Miao, H. Du, D. Lai, Y. Yang, Z. Lian, How do people set air conditioning temperature setpoint in urban domestic–Behavior model in Chinese three climate zones based on historical usage data, Energ. Buildings 284 (2023) 112856, https://doi.org/10.1016/j.enbuild.2023.112856.
[95] J. Caballero-Peña, G. Osma-Pinto, J.M. Rey, S. Nagarsheth, N. Henao, K. Agbossou, Analysis of the building occupancy estimation and prediction process: A systematic review, Energ. Buildings 313 (2024) 114230, https://doi.org/10.1016/j.enbuild.2024.114230.
[96] Y. Jin, D. Yan, A. Chong, B. Dong, J. An, Building occupancy forecasting: A systematical and critical review, Energ. Buildings 251 (2021) 111345, https://doi.org/10.1016/j.enbuild.2021.111345.
[97] R. Andersen, V. Fabi, J. Toftum, S.P. Corgnati, B.W. Olesen, Window opening behaviour modelled from measurements in Danish dwellings, Build. Environ. 69 (2013) 101–113, https://doi.org/10.1016/j.buildenv.2013.07.005.
[98] M. Foster, T. Oreszczyn, Occupant control of passive systems: the use of Venetian blinds, Build. Environ. 36 (2001) 149–155, https://doi.org/10.1016/S0360-1323(99)00074-8.
[99] T. Verma, P. Gopalakrishnan, Categorising the existing irradiance based blind control occupant behavior models (BC-OBMs) using unsupervised machine learning approach: A case of office building in India, Energ. Buildings 279 (2023) 112700, https://doi.org/10.1016/j.enbuild.2022.112700.
[100] J. Lyu, Y. Shi, H. Du, Z. Lian, Sex-based thermal comfort zones and energy savings in spaces with joint operation of air conditioner and fan, Build. Environ. 246 (2023) 111002, https://doi.org/10.1016/j.buildenv.2023.111002.
[101] H. Imagawa, H.B. Rijal, M. Shukuya, Development of integrated occupant-behavioural stochastic model including the fan use in Japanese dwellings, Energ. Buildings 226 (2020) 110326, https://doi.org/10.1016/j.enbuild.2020.110326.
[102] P.N. Duhirwe, J. Ngarambe, G.Y. Yun, Geographically extended occupant clothing behavior model using convolutional neural networks with hyperband technique, Journal of Building Engineering 49 (2022) 104023, https://doi.org/10.1016/j.jobe.2022.104023.
[103] B. Becerik-Gerber, G. Lucas, A. Aryal, M. Awada, M. Bergés, S.L. Billington, O. Boric-Lubecke, A. Ghahramani, A. Heydarian, F. Jazizadeh, R. Liu, R. Zhu, F. Marks, S. Roll, M. Seyedrezaei, J.E. Taylor, C. Höelscher, A. Khan, J. Langevin, M.L. Mauriello, E. Murnane, H. Noh, M. Pritoni, D. Schaumann, J. Zhao, Ten questions concerning human-building interaction research for improving the quality of life, Build. Environ. 226 (2022) 109681, https://doi.org/10.1016/j.buildenv.2022.109681.
[104] IEA-EBC Publications |Annex66, http://www.annex66.org/?q=Publication.
[105] Publications || IEA EBC || Annex 79, https://annex79.iea-ebc.org/publications.
[106] M. Schweiker, E. Ampatzi, M.S. Andargie, R.K. Andersen, E. Azar, V. M. Barthelmes, C. Berger, L. Bourikas, S. Carlucci, G. Chinazzo, L.P. Edappilly, M. Favero, S. Gauthier, A. Jamrozik, M. Kane, A. Mahdavi, C. Piselli, A.L. Pisello,

A. Roetzel, A. Rysanek, K. Sharma, S. Zhang, Review of multi-domain approaches to indoor environmental perception and behaviour, Build. Environ. 176 (2020) 106804, https://doi.org/10.1016/j.buildenv.2020.106804.

[107] F. Zhang, R. de Dear, Impacts of demographic, contextual and interaction effects on thermal sensation—Evidence from a global database, Build. Environ. 162 (2019) 106286, https://doi.org/10.1016/j.buildenv.2019.106286.

[108] Q. Zhao, Z. Lian, D. Lai, Thermal comfort models and their developments: A review, Energy Built Environ. 2 (2021) 21–33, https://doi.org/10.1016/j.enbenv.2020.05.007.

[109] European Committee for Standardization (CEN). (2019). EN 16798-1:2019, Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

[110] R. de Dear, J. Xiong, J. Kim, B. Cao, A review of adaptive thermal comfort research since 1998, Energ. Buildings 214 (2020) 109893, https://doi.org/10.1016/j.enbuild.2020.109893.

[111] R.F. Rupp, J. Kim, E. Ghisi, R. de Dear, Thermal sensitivity of occupants in different building typologies: The Griffiths Constant is a Variable, Energ. Buildings 200 (2019) 11–20, https://doi.org/10.1016/j.enbuild.2019.07.048.

[112] H. Ning, Z. Wang, Y. Ji, Thermal history and adaptation: Does a long-term indoor thermal exposure impact human thermal adaptability? Appl. Energy 183 (2016) 22–30, https://doi.org/10.1016/j.apenergy.2016.08.157.

[113] Y. Liu, Y. Dong, C. Song, Y. Wang, L. Liu, J. Liu, A tracked field study of thermal adaptation during a short-term migration between cold and hot-summer and warm-winter areas of China, Build. Environ. 124 (2017) 90–103, https://doi.org/10.1016/j.buildenv.2017.07.022.

[114] J. Kim, R. de Dear, T. Parkinson, C. Candido, Understanding patterns of adaptive comfort behaviour in the Sydney mixed-mode residential context, Energ. Buildings 141 (2017) 274–283, https://doi.org/10.1016/j.enbuild.2017.02.061.

[115] H. Yan, Y. Mao, L. Yang, Thermal adaptive models in the residential buildings in different climate zones of Eastern China, Energ. Buildings 141 (2017) 28–38, https://doi.org/10.1016/j.enbuild.2017.02.016.

[116] R. Yao, B. Li, J. Liu, A theoretical adaptive model of thermal comfort – Adaptive Predicted Mean Vote (aPMV), Build. Environ. 44 (2009) 2089–2096, https://doi.org/10.1016/j.buildenv.2009.02.014.

[117] P. Ole Fanger, J. Toftum, Extension of the PMV model to non-air-conditioned buildings in warm climates, Energ. Buildings 34 (2002) 533–536, https://doi.org/10.1016/S0378-7788(02)00003-8.

[118] Z. Wang, R. de Dear, M. Luo, B. Lin, Y. He, A. Ghahramani, Y. Zhu, Individual difference in thermal comfort: A literature review, Build. Environ. 138 (2018) 181–193, https://doi.org/10.1016/j.buildenv.2018.04.040.

[119] S. Karjalainen, Thermal comfort and gender: a literature review, Indoor Air 22 (2012) 96–109, https://doi.org/10.1111/j.1600-0668.2011.00747.x.

[120] L. Lan, Z. Lian, W. Liu, Y. Liu, Investigation of gender difference in thermal comfort for Chinese people, Eur. J. Appl. Physiol. 102 (2008) 471–480, https://doi.org/10.1007/s00421-007-0609-2.

[121] N. Wongsurawat, B.B. Davis, J.E. Morley, Thermoregulatory Failure in the Elderly, J. Am. Geriatr. Soc. 38 (1990) 899–906, https://doi.org/10.1111/j.1532-5415.1990.tb05708.x.

[122] N.A.S. Taylor, N.K. Allsopp, D.G. Parkes, Preferred Room Temperature of Young vs Aged Males: The Influence of Thermal Sensation, Thermal Comfort, and Affect, The Journals of Gerontology: Series A 50A (1995) M216–M221, https://doi.org/10.1093/gerona/50A.4.M216.

[123] T. Ma, J. Xiong, Z. Lian, A human thermoregulation model for the Chinese elderly, J. Therm. Biol 70 (2017) 2–14, https://doi.org/10.1016/j.jtherbio.2017.08.002.

[124] S.M. Horvath, C.E. Radcliffe, B.K. Hutt, G.B. Spurr, Metabolic Responses of Old People to a Cold Environment, J. Appl. Physiol. 8 (1955) 145–148, https://doi.org/10.1152/jappl.1955.8.2.145.

[125] J. Nakano, S. Tanabe, K. Kimura, Differences in perception of indoor environment between Japanese and non-Japanese workers, Energ. Buildings 34 (2002) 615–621, https://doi.org/10.1016/S0378-7788(02)00012-9.

[126] L. Arakawa Martins, V. Soebarto, T. Williamson, A systematic review of personal thermal comfort models, Building and Environment 207 (2022) 108502. 10.1016/j.buildenv.2021.108502.