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Outdoor thermal comfort research in transient conditions: A narrative literature review

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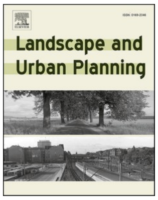

Review Article

Outdoor thermal comfort research in transient conditions: A narrative literature review

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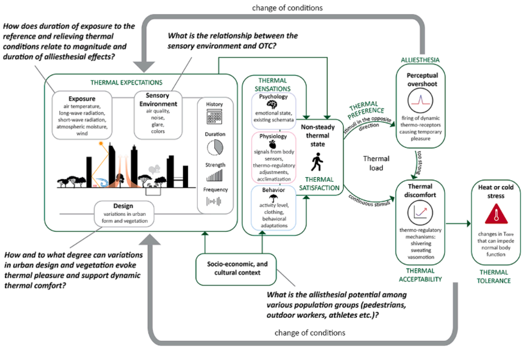
HIGHLIGHTS

- This study clarifies and summarises concepts on outdoor thermal comfort (OTC) research;
- Provides potential future research directions on OTC in four different fields;
- Examines relevant link between human thermal state and external built environment.

GRAPHICAL ABSTRACT



ABSTRACT

In recent years, urban planners and designers are paying greater attention to Outdoor Thermal Comfort (OTC) studies due to the imminent threat of the Urban Heat Island and climate change on human health. Historically, indoor thermal comfort research assumed steady-state conditions, centralizing on the concept of thermal neutrality to determine optimal environmental parameters. Such research pivoted to investigating how non-steady-state, transient environmental conditions influence comfort. Recent studies underscore the usefulness of positive alliesthesia in providing a productive framework for OTC evaluation. In this article we first clarify the concepts related to thermal comfort-related terms, scales, and models in the literature. Then, we propose four research questions that we believe are important for the research of thermal transient sensations. To answer them, we present the state of current research and gaps for the field and provide directions that could advance the knowledge on dynamic OTC.

1. Introduction

Concerns on improving outdoor thermal comfort (OTC) are becoming more widespread in cities, especially in the context of global warming and growing climate extremes. Urban heating and rising health risks associated with increasing sedentary lifestyles are engendering shifts in planning measures towards improving urban walkability and liveability. Urban landscapes are predominantly human managed, incorporating a spectrum of grey to green infrastructure. The types and location of such urban forms shape meso- and micro- environmental processes, and ultimately, how individuals feel and perceive them traversing through these landscapes. Assessing these individual

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perceptions would allow an in-depth understanding between the human health and wellbeing, and the surrounding environment.

There is neither a consistent nor comprehensive framework to evaluate OTC and guide research opportunities. OTC concepts utilised in current studies tend to use terms such as 'thermal acceptability', 'thermal neutrality', and 'thermal comfort' interchangeably. Existing models cannot accurately estimate OTC (Shooshtarian, 2019); current studies generally neglect psychological, socio-economic, and cultural factors (Nazarian & Lee, 2021), and assume steady-state conditions for outdoor subjects (Aljawabra & Nikolopoulou, 2010).

The objectives of this narrative review are firstly to critically examine the relationship between concepts related to thermal comfort, and to provide definitions and most common scales used in scientific studies. Secondly, we discuss the most common OTC models and explain how thermal alliesthesia can be a useful framework to evaluate dynamic OTC. Finally, we propose four research questions which, if answered, we believe would improve understanding of how alterations of urban landscapes shape dynamic thermal experiences of urbanites. To answer these questions, we present the current state of literature on the subject, exposing existing gaps and providing suggestions on how those gaps can be filled. This study's literature search process is summarised by a flowchart (Appendix A). We input shortlisted keywords related to OTC (Appendix B) into academic citation databases, e.g., Google Scholar and Web of Science, and applied citation tracking from key studies. A total of 102 publications were selected for this review.

1.1. Relationships between the thermal comfort concepts

The most utilised definition of thermal comfort is provided by ASHRAE Standard 55 (2010), i.e., the '… condition of mind that expresses satisfaction with the thermal environment' (Table 1). Such a definition emphasises the importance of 'satisfaction'. In application, it is derived from the middle of the thermal sensation scale (ASHRAE Standard 55, 2010; Shooshtarian, 2019; Brager et al., 1993). However, concepts like 'thermal sensation' and 'thermal comfort' should not be used interchangeably because they describe two distinct attitudes toward the microclimate (Auliciems, 1981; Shooshtarian & Rajagopalan, 2017). Thermal sensation vote (TSV) identifies thermal stimulus strength without providing information about the individual's perception towards it; while thermal comfort qualitatively describes individual's attitude towards the stimulus (De Dear, 2011; Vellei & Le Dréau, 2019). In steady-state environmental conditions, overall TSV, acceptability, and comfort are closely related. However, there was no relationship between TSV and these evaluations in non-uniform environments in Zhang & Zhao, 2008, 2009 study. Terms such as thermal expectations, thermal preference, and thermal pleasure from relieving thermal overloads become more prominent in influencing affective judgments (Nikolopoulou & Steemers, 2003; Nazarian et al., 2021, Shooshtarian & Rajagopalan, 2017).

'Thermal expectations' refer to the individual's beliefs of what the thermal environment should be like. These can be influenced by seasonality, short- and long-term history, and other contextual factors (Nikolopoulou & Steemers, 2003). For instance, people expect less fluctuations in climate-controlled environments compared to natural ones. A match of thermal expectations with actual conditions results in 'thermal satisfaction' (De Dear and Schiller Brager, 2001). Fanger (1972) used the concept of thermal (dis)satisfaction in predicted mean vote (PMV) model, allowing identification of percentages of dissatisfied (PPD) individuals with the thermal environment. According to Fanger, the lowest PPD equals to 5% when PMV = 0. However, Fanger's concept was not empirically tested and is merely based on the assumption that people whose perception falls outside the middle range of the TSV scale will be dissatisfied. Upon testing, however, this model did not hold true for outdoor environments. OTC studies show wide discrepancies between PPD and actual percentage of dissatisfied (APD) (Lai et al., 2017). For instance, Nikolopoulou & Steemers' (2013) study found an average

Table 1
List of terms and definitions extracted across thermal comfort literature.

Concepts	Definitions from the literature
Thermal comfort	'[…] that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.' (ASHRAE Standard 55, 2010, p.3) 'Subjective indifference to the thermal environment.' (Bligh & Johnson, 1973, p.582) 'a recognisable state of feeling' is associated with happiness, pleasant feelings and health. (Gagge et al., 1967, p.1)
Thermal neutrality	Thermal index values at which the majority of people feel neither cold nor warm. (Zhang & Zhao, 2008; Shooshtarian & Rajagopalan, 2017) '[…] thermal index value corresponding with a mean vote of neutral on the thermal sensation scale.' (ASHRAE Standard 55, 2010, p.3) 'The range of ambient temperatures, associated with specified water vapor pressure, air velocity, and radiant exchange, within which 80% of active people do not complain of the thermal environment.' (Bligh & Johnson, 1973, p.582)
Thermoneutral zone	'The range of ambient temperature at which temperature regulation is achieved only by control of sensible heat loss i.e., without regulatory changes in metabolic heat production or evaporative heat loss.' (Bligh & Johnson, 1973, p.584)
Thermal sensation	'a conscious feeling commonly graded into the categories cold … neutral … hot.' (ASHRAE Standard 55, 2010, p.3; Brager et al., 1993) '[…] is related to how people 'feel' and is therefore a sensory experience and a psychological phenomenon.' (Parsons, 2014, p.83) The body's sensory experience devoid of the affective, evaluative, or preferential assessment of the experience towards the thermal environment. (Schweiker et al., 2017)
Thermal expectation	'what the environment should be like, rather than what it actually is' based on the past thermal experience. (Nikolopoulou & Steemers, 2003, p.97)
Thermal acceptability	An environment which 80% of individuals find to be thermally acceptable. (ASHRAE Standard 55, 2010; Berglund, 1979; Brager et al., 1993) 'What an individual is agreeable to, or approves of.' (Brager et al., 1993, p.27)
Thermal satisfaction	'matching actual thermal conditions in a given context and one's thermal expectations of what the indoor climate should be like in that same context.' (De Dear and Schiller Brager, 2001, p.101) Environmental condition when PPD is the lowest (minimum value of 5%). (Fanger, 1972)
Thermopreferendum, or thermal preference	'The thermal conditions that an individual organism or a species selects for its ambient environment in natural or experimental circumstances.' (Bligh & Johnson, 1973, p.584) An ideal condition an individual would favour in the thermal environment. (Brager et al., 1993; De Dear and Schiller Brager, 2001)
Thermal alliesthesia	'the phenomenon by which a given stimulus can create pleasant/unpleasant sensation, per the individual's internal state.' (Cabanac, 1971, p.1107; De Dear, 2010) '[…] the changed perception of a given peripheral

(continued on next page)

Table 1 (*continued*)

Concepts	Definitions from the literature
	stimulus resulting from the stimulation of internal sensors. Positive alliesthesia indicates a change to a more pleasurable sensation, negative alliesthesia a change to a less pleasurable one.' (Bligh & Johnson, 1973, p.568)
	'state of […] pleasure associated with the relief of thermal discomfort under transient conditions.' (Zhang and Zhao, 2008, p.50)

PPD of 66% while the APD was close to 10%.

'Thermal preference' identifies the ideal thermal environment for individuals in the context of the actual conditions (Heng & Chow, 2019). These often differ from what is predicted as optimal by heat balance models (Höppe, 2002). Depending on the season, people prefer to feel warmer or cooler than neutral in temperate climates (Nikolopoulou & Steemers, 2003), while people generally prefer feeling cooler in warm and hot climates (Heng & Chow, 2019; Middel et al., 2016).

Thermal neutrality is another important concept as it often appears as a middle point of many scales in thermal comfort studies, identifying the condition when people feel neither cold nor warm, or do not complain about their thermal environment (Table 1). This concept should not be confused with a thermoneutral zone (TNZ), environmental conditions at which the human body does not engage sudomotor or thermogenic processes (sweating, shivering) to thermoregulate.

The above concepts can persist for long and short time periods; 'thermal pleasure', however, is a transient condition requiring a specific climatic context and physiological conditions. Several researchers associate thermal pleasure as derivable from some forms of thermal discomfort alleviation (De Dear, 2011; Parkinson et al., 2015). In section 2.4, we uncover the importance of thermal pleasure in OTC studies.

1.2. *Types of OTC scales*

Measurement scales capture appropriate information about individuals and their subjective judgments of the environment. They are used extensively to assess individuals' thermal state and preferences in relation to surrounding thermal conditions. In Fig. 1, we compile measurement scales used to create questionnaires, improving models and methodology for thermal comfort research. Three types of scales determine personal thermal states in comfort studies: (1) descriptive, (2) affective, and (3) preferential judgement scales. Gagge et al. (1967) first utilised the descriptive and affective scales. They used 7-point thermal sensation scales to record both physiological thermal sensation, and 4-point scales of comfort sensation for affective thermal comfort of individuals.

Descriptive scales are used to determine one's present thermal state, precluding subjective assessments. The 'neutral' point here refers to an absence of feeling 'hot' or 'cold', and it should not assume comfort. This differs from other studies where the middle point of indifference or neutrality is deemed as 'comfortable' (e.g., Houghton & Yaglou, 1923; Bedford & Chrenko, 1974). Affective scales focus on the affective dimension of thermal comfort. They include associated words like (dis) pleasure (Winslow et al., 1937), (dis)comfort (Gagge et al., 1967) and (dis)satisfaction (ASHRAE Standard 55, 2010). Given that neutral sensations do not necessarily correspond to thermal comfort, the combination of a descriptive thermal sensation scale, affective and preference rating is better able to indicate thermal comfort (Shahzad et al., 2018). This is where additional affective scales, including thermal satisfaction, thermal tolerance and thermal acceptability might be useful to identify nuanced thermal judgments. The thermal satisfaction scale may be in the form of 7-point or dual-point scales. Similarly, for thermal tolerance and thermal acceptability, binary scales, 4-point and 5-point measures of bearability may be used. Lastly, preferential judgement scales typically follow descriptive and affective scales, to ascertain people's

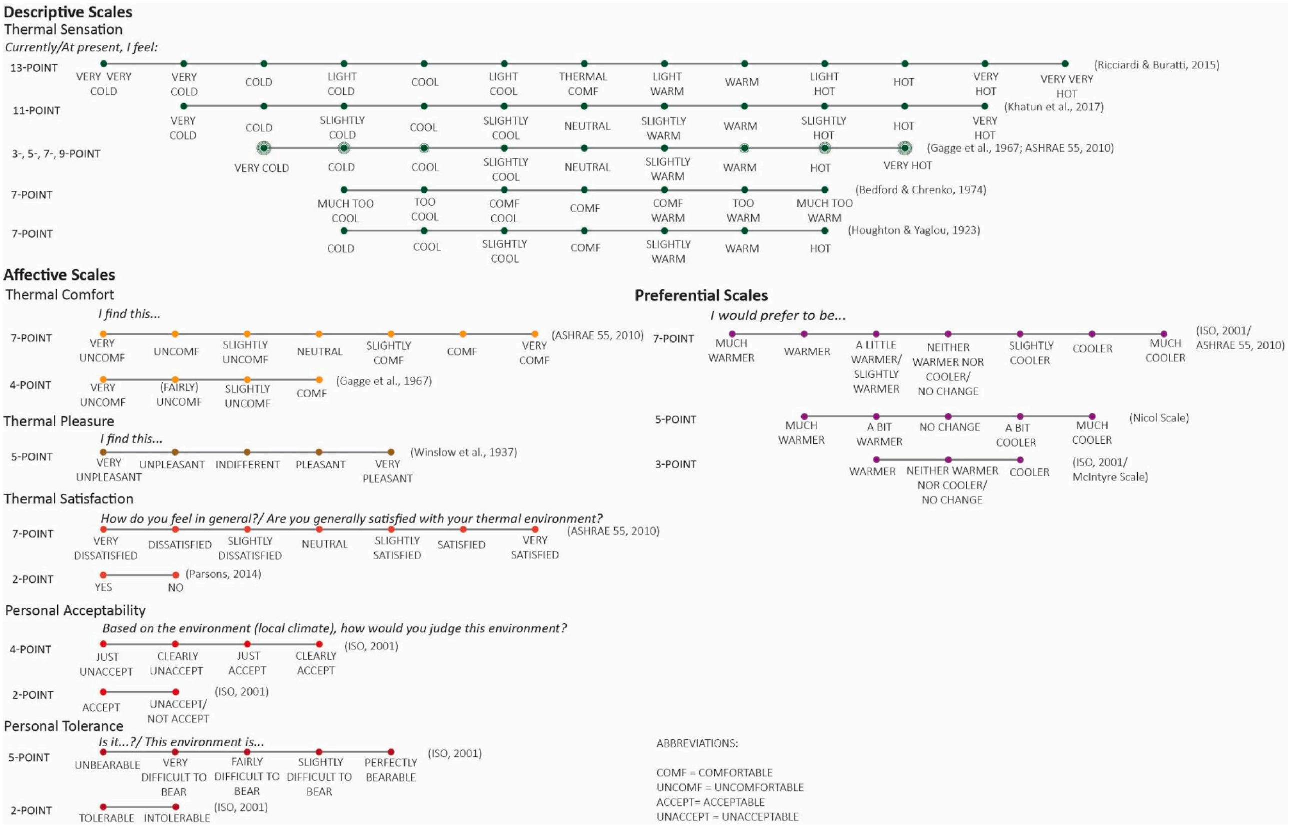

Fig. 1. Types of measurement scales - descriptive, affective, and preferential - used in thermal comfort questionnaires.

desired sensation (Humphreys and Hancock, 2007).

Although most thermal perception scales utilised today are categorical, continuous scales can also be used. While successive categorical scales are fixed, continuous scales attempt to remove that limitation by removing discrimination. Some researchers have challenged the underlying assumption of equidistance between each scale marker in categorical scales, wherein the sensations described are perceived to be uniform across individuals (Sama & Lawrence, 2019). Schweiker et al. (2017) established that a one-dimensional, linear relationship between thermal sensation and climatic variables is false; especially in the case for extremities ('very cold' or 'very hot') where individuals perceived intervals to be either bigger or smaller between 'cold' and 'cool' and 'warm' and 'hot', compared to sensations around 'neutral'. In fact, McIntyre (1980) found that continuous scales offer smaller intervals of values, allowing for greater differentiated evaluation for individuals' thermal sensation. In this way, it is useful to think of thermal sensation as a psychological continuum.

Nevertheless, discrete scales have been most prominent in current methods, with either 3-, 5-, 7-, and 9-point scales used. However, different scales should be adopted under specified conditions since climatic regions are known to affect thermal sensation and comfort. For example, Schweiker et al. (2017) recommend that 7-point descriptive scales be applied in temperate climates, while 9-point scales with added 'very cold' and 'very hot' categories are recommended for extreme climate conditions. While some studies have suggested up to a 13-point scale with smaller intermediate intervals (Ricciardi & Buratti, 2015), it is not advisable to use too many categories due to selection fatigue (Wang et al., 2018).

Overall, nuances in how scales are conceptualised and applied are known to shape experimental results (Wong & Khoo, 2003; Schweiker et al., 2020a). For instance, in Griffiths and McIntyre (1974) study, ambient temperature (T_a) range for the comfort zone was wider under transient conditions when individuals were asked based on the two-point acceptability scale, compared to conventionally deriving acceptability from TSVs and Fanger's PMV/PPD (Hensen, 1990). Depending on the Bedford, ASHRAE and McIntyre preference scale applied for thermal acceptability, PPD would vary from 21% to 76% (Wong & Khoo, 2003). Given that those voting on the extremes of the 7-point ASHRAE and Bedford scales may consider their environment to be acceptable, it is meaningful to use scales in combination with thermal sensation, preference, and acceptability votes.

Lastly, it is critical to validate scales according to local climatic conditions and cultural backgrounds. In warmer climates, associated words such as 'cold' and 'cool' may be related to comfortability and acceptability, and vice versa for colder climates (Schweiker et al., 2020b). Alongside different language semantics, expectation and acclimatization to local climates contributes to ratings of thermal sensation and preferences. Khatun et al. (2017) shows that Bengali-speaking individuals perceive 'neutral' for comfortability due to linguistic differences, and respondents are accustomed to high T_a in a hot and humid climate. Ratings of thermal sensation may depend on their acclimatization, influenced by occupation and expectations (Banerjee et al., 2020). Thus, a combination of appropriate descriptive, affective and preferential scales, along with understanding of local climates and respondents' experiences would provide a more holistic picture of people's thermal comfort.

1.3. Models for OTC

Over 165 thermal indices were developed to assess human thermal conditions, varying in number and combinations of environmental and psychological parameters, rationale, and complexity of the model (De Freitas & Grigorieva, 2015; Staiger et al., 2019; Enescu, 2019). A recent study has identified three selection criteria of the appropriate thermal index for human biometeorological research: it has to be (1) rational: based on the modelling of heat exchanges between the human body and environment; (2) taken in a form of the equivalent temperature of a reference environment, where mean radiant temperature (T_{mrt}) = T_a, to enable universal understanding; and (3) applicable worldwide for ease of cross-comparisons (Staiger et al., 2019).

Based on these, authors identified four suitable models: Universal Thermal Climate Index (UTCI), Perceived Temperature (PTj), Physiologically Equivalent Temperature (PET), and rational Standard Effective Temperature (SET*). Inter-model comparisons show that PET overestimates thermal sensation in hot and dry environments due to a fixed clothing value of 0.9 clo and its similarity to standard operative temperature. In the cold, PET is also higher compared to other indexes due to the model's limitations in simulating heat fluxes through skin. SET* and PTj are very similar in warm environments because they have the same thermo-physiological foundation and small differences in clothing value, but different in the cold due to changes in clothing insulation for PTj. UTCI has the highest variability during colder periods and lower values in summer, since it is based on the adaptive clothing model reflecting behavioural adaptation, while the other indices have fixed values (Staiger et al., 2019).

Thermal comfort indices are commonly linked to descriptive, affective, and preferential attitudes of human subjects to identify thermal acceptability, comfort, and satisfaction thresholds defined by regression or probit analysis (Shooshtarian & Rajagopalan, 2017). Despite the wide variability of thermal indices, a scientific consensus is present that models based solely on heat balance or adaptive thermal comfort disallow comprehensive evaluation of OTC (Nikolopoulou & Steemers, 2003; Shooshtarian, 2019). Most studies used OTC models assuming steady-state conditions, rarely attainable in heterogeneous urban environments. Non-steady-state or dynamic thermal comfort models are applicable in environmental transients, with differences in meteorological conditions, activities, or clothing on a timescale of minutes. Thus, dynamic models explore physiological and/or perceptual changes in dynamic microclimates over a short period of time. In such cases, short-term thermal history becomes an important factor (Katavoutas et al., 2015).

Even though non-steady-state models are less widespread in outdoor settings and often lack experimental data for validation (Lai & Chen, 2016), several recent attempts have utilised dynamic OTC models for outdoor environments. For instance, the Instationary Munich Energy Balance Model (IMEM) accounts for sensible heat storage in the body to estimate body temperature changes. It uses inputs from a steady-state model for initial values of mean skin temperature (T_{sk}) and mean core temperature (T_{core}). It further uses numerical integration through time steps to calculate body temperature changes. Achieved values are directly input for the next time step (Katavoutas et al., 2015). Zhang et al. (2020) showed that PET and UTCI had a good linear relationship with mean TSV for participants at rest but performed poorly for walking subjects. They significantly improved both models by incorporating metabolic rate into the equation. Lai et al. (2017) developed a dynamic OTC model based on the indoor dynamic thermal sensation (DTS) models, considering thermal load, mean T_{sk} and the change rate of the mean T_{sk}. Their subjects were standing outdoors for an hour under various environmental parameters and assumed a low metabolic rate. Authors validated the model based on experimental data they collected for a city in a similar climate. Zhou et al. (2020) then compared the four dynamic thermal comfort models, namely: (1) the DTS model, (2) the UC Berkeley model, (3) Lai's model for outdoor thermal environments, (4) Zhou's model for vehicular environments. Among these, Lai's and Zhou's models were more accurate in predicting TSV in outdoor environments. In addition to including mean T_{skin} differences, Zhou's model integrated sudden changes in solar radiation on TSV by including differences in facial T_{sk}. The model showed that depending on whether subjects face the sun or not, their TSV can differ by up to two units (Zhou et al., 2021).

In summary, dynamic OTC models help to address some shortcomings of steady-state OTC by incorporating differences in T_{sk} over time, showing a better agreement for predicting outdoor TSV. However, more studies are needed to investigate the relationship between the affective and preferential judgments in addition to descriptive. A framework of thermal alliesthesia is useful in explaining the dynamic thermal comfort in transient environments (Shooshtarian, 2019).

1.4. Thermal alliesthesia to explain OTC in transient conditions

The hedonic aspect of thermal comfort in non-steady-state conditions can be explained through the framework of thermal alliesthesia. While walking or performing activities in the city, individuals experience a variety of conditions. The body thus constantly adapts its physiological responses and behaviours to maintain an optimal internal temperature. When an individual is subjected to environmental stimuli that could help achieve optimal conditions, they perceive it as pleasant (imagine a relief from entering an air-conditioned store after a walk on a sweltering summer day). However, when the stimulus adds to the thermoregulatory load, it is perceived as unpleasant. This phenomenon is described as thermal alliesthesia (Cabanac, 1979). Pleasant or unpleasant sensations tend to be the strongest at the immediate point of change from one environmental condition to another, then flatten once the condition stabilises. In contrast to single-point measurement studies of TSV over T_a, which derives the point of neutrality; for alliesthesia, preceding conditions are most important, and rate of change between the TSV points determines the strength and duration of thermal pleasure (Parkinson et al., 2015).

In physiological terms, alliesthesia intensities depend on magnitudes of deviation from the optimal state and the rate of change in T_{sk} (De Dear, 2011; Vellei & Le Dréau, 2019). Moderate thermal alliesthesia occurs when thermal perception is within the TNZ, and strong thermal alliesthesia occurs when body adaptation mechanisms are involved (e.g., sweating, shivering) (Liu et al., 2020). Once thermal balance is achieved, the stimulus no longer causes pleasant or unpleasant feelings. The time taken to return to steady-state conditions depends on the magnitude of deviation of microclimatic variables from the optimal. In an experiment where participants were exposed to T_a of 37 °C and 34 °C at 70% relative humidity (RH), and then transferred to 6–12 °C cooler conditions with 55% RH, results showed that it took about one hour to reach neutrality after 37°C and half the time after 34 °C exposure (Nagano et al., 2005). Since thermal alliesthesia depends on the current internal state of an individual, the same environmental stimuli can be perceived as pleasant or unpleasant (De Dear, 2011; Son & Chun, 2018; Liu et al., 2020). Moreover, 'very comfortable' feelings only occur when thermal stress is relieved by local stimulation in the direction towards restoring equilibrium (Arens et al., 2006). Thus, very comfortable conditions or pleasantness are unattainable under neutral conditions and require a certain degree of thermal discomfort.

Alliesthesia is caused by the firing of the dynamic thermoreceptors (De Dear, 2011), with firing rates of thermoreceptors being 5–10 times stronger during environmental transients compared to stable conditions. This condition is reflected in thermal sensations and thermal comfort evaluations as an 'overshoot' that precedes physiological changes in the body (Arens et al., 2006). A study using an electroencephalogram (EEG) to explore delays in physiological responses found a significant increase in thermal comfort within a group subjected to thermal step-changes compared to the control group. The alliesthesial effect from step-changes on brain activity was similar to the effect from meditation or music, and lasted for 20 min (Son & Chun, 2018). Thermal overshoots were stronger for larger differences between the conditions, and more pronounced for the step-down changes (from warm to cool) (Mishra et al., 2016). Several studies found that temperature changes of 7–9 °C evoke thermal pleasure, but steps above 10 °C did not trigger alliesthesia (Son & Chun, 2018). Moreover, sensations also change depending on which body part is affected. For instance, face cooling has a stronger effect in warm environments and body warming in cool temperatures. Targeted warming/cooling of body parts has a stronger effect compared to the application to the whole body (Cotter & Taylor, 2005).

In contrast to temporal thermal alliesthesia, which is affected by immediate microclimatic conditions, seasonal thermal alliesthesia is based on long-term user experiences. For instance, in summer and in warm climates, people prefer feeling cooler than neutral, while in winter, they experience pleasure from feeling warmer (Hwang et al., 2009; Liu et al., 2020; Schweiker et al., 2020a).

2. Research directions for thermal transients

Based on the narrative literature review, we formulated four research questions that we believe would help to advance the field of dynamic OTC. Below we present the research questions, current available research on the subject, expose research gaps, and suggest potential pathways to advance the field. They highlight the importance of considering holistic exposure to the four environmental stimuli together with physiological parameters and subjective judgments; the influence of the other sensory experiences on thermal comfort; impact of urban forms on thermal pleasure; and the need to integrate socio-economic, and cultural dimensions to improve existing OTC models.

2.1. How does duration of exposure to the reference and relieving thermal conditions relate to magnitude and duration of alliesthesial effects?

Complex urban landscapes provide heterogeneous exposure to environmental stimuli. In such conditions, strength of stimuli, duration of exposure, and thermal history all affect dynamic OTC. These factors have been explored in two research areas.

First, scholars analysed dynamic thermal comfort in controlled environments with predefined step-changes in microclimate variables, usually with simultaneous monitoring of physiological parameters, and descriptive and affective judgments (Du et al., 2014; Parkinson et al., 2015; Yu et al., 2016). In doing so, they examined the effects of T_a changes, and occasionally humidity. Air movement and radiation are often held constant. Indoor thermal comfort literature explores the effect of draughts and fans, but studies show that natural wind might have a different effect (Mishra et al., 2016).

Second, scholars incorporate quasi-experimental studies in outdoor environments, with single-point microclimate measurements to derive steady-state thermal comfort index values correlated with descriptive and affective thermal judgments (Middel et al., 2016; Banerjee et al., 2020). Here, effects of T_a, short- and long-wave radiation, wind, and humidity are considered. These studies mostly concentrate on defining neutral and acceptable thermal ranges by collecting survey data across climates and seasons. They rarely collect physiological data.

To have an in-depth understanding of how the changes in duration and magnitude of exposure to various microclimates are related to the magnitude and duration of alliesthesial effect, simultaneous monitoring of physiological and psychological states in complex urban settings is necessary. Recently, several studies investigated dynamic thermal comfort and thermal pleasure outdoors. Liu et al. (2020) explored dynamic thermal pleasure by subjecting participants to various stimuli at different metabolic rates while collecting their thermal judgments. Alliesthesia occurred after local thermal stimulation was applied in the direction towards thermal equilibrium. Too large of a difference in thermal sensations, however, did not evoke thermal pleasure, as they were pushing thermal balance out of the comfort zone towards the opposite end (Liu et al., 2020). Lau et al. (2019) explored the effect of short-term thermal history on TSV lag for subjects walking on Hong Kong streets. They found that streets with higher T_{mrt} that followed more shaded ones had lower TSV votes, indicating potential lasting effect of thermal history. In an experiment in a transitional covered area in Hong Kong, Zhang et al. (2020) found that when the effect of shortwave radiation is minimal, air velocity becomes the most influential environmental stimulus on pedestrian thermal sensations and heat storage.

Advances in wearable sensing technology enables physiological data collection during outdoor field studies, enabling a better understanding of the relationship between environmental stimuli, physiological response, and thermal perception. Hastings et al. (2020) utilised infrared sensors on outdoor workers at an airport, concluding that measurement of T_{sk} alone can be an indicator of heat health. Additionally, thermal imagery should be paired with wearable sensors measuring other physiological parameters to accurately estimate OTC. Nakayoshi et al. (2015) used several wearable sensors to measure both physiological and environmental parameters with participants traversing through various local climate zones (LCZ). They found a relationship between sweat rate and types of LCZ, indicating that shifts in urban form and designs affect physiological and affective responses. Participants felt more comfortable along greener and/or more shaded areas. In studies combining climate chamber and outdoor experiments using wearable wristwatches with iButton temperature sensors, T_{sk} was a stronger predictor of thermal satisfaction compared to heart rate. Dissatisfaction occurred with decreases in the difference between the T_a at wrist and T_{sk} (Nazarian et al., 2021). Nazarian and Lee (2021) noted that technological advancements offer lower-cost, crowd-source sensors, and devices. Developments in the Internet of Things sensors and crowd-sourced data allow for higher spatial resolution of environmental data, thus increasing the potential for research.

A standardised approach to accurately measure physiological parameters in outdoor environments is currently lacking. Measurement of T_{core}, and accounting for individual physiological heterogeneity remain challenging for OTC research. Physiological variables requiring measurement should be selected depending on research objectives. T_{core} monitoring is important to understand the potential for heat stress, while changes in T_{sk} can better predict thermal sensations and thermal pleasure. These considerations could yield important data to calibrate OTC models, especially for hot-humid climates where validation is scarce.

2.2. What is the relationship between the sensory environment and OTC?

Indoor thermal comfort studies conclude that sensory factors like air quality, sensation of glare, colour, and noise affect thermal perceptions (Mishra et al., 2016). We opine this is a crucial OTC research area, considering urban heterogeneity and emerging policies aimed to address heating in urban landscapes. For instance, many cities consider albedo modification on roads or walkways to reduce the UHI effect, with some already implementing pilot programs in city neighbourhoods (EPA Heat Island Reduction Program, 2018). Modelling (Erell et al., 2014) and measurement studies (Middel et al., 2020) show that coatings of reflective paint can adversely affect OTC due to increased T_{mrt}. Using human subjects to investigate the effect of reflective pavements and possible resulting glare on thermal comfort and alliesthesia is underexplored. Tan & Fwa (1997) evaluated thermal and glare comfort of granite, concrete, and asphalt pavements of military parade squares in Singapore, and found that soldiers perceived alternative pavement types more thermally comfortable than asphalt. Glare-wise, all pavement types were rated similarly in dry conditions. However, when wet, glare comfort assessments dipped for all surfaces, with asphalt performing the poorest. More studies are needed to assess performance of novel cool coatings in both dry and wet, and sun exposed and shaded conditions.

Alliesthesia studies demonstrate that visual sensory input affects thermoregulatory behaviour and perception of thermal comfort. Lam et al. (2020) elucidated a positive correlation between TSV and sun sensation, with respondents feeling hotter when it is brighter. Louafi et al. (2017) also found that microclimate was perceived as pleasant in tree-shaded areas with soft daylight for a hot, dry climate in Algeria. Solar radiation was perceived neutral in areas with high tree coverage but perceived as too strong in areas without trees. This preference was similarly reflected in a higher occupancy of tree-covered recreational spaces.

Furthermore, changes in noise and air pollution yield similar effects as changes in temperature (Mishra et al., 2016). Lau and Choi (2021) found significant relationships between aesthetic and acoustic satisfaction and TSV and OTC in Hong Kong, with participants who were satisfied with aesthetic and acoustic environments having lower TSV and feeling more comfortable.

Lastly, some studies investigate air quality in relation to OTC. Indoor experiments established relationships between TSV and perception of air quality (Liu et al., 2019). However, no outdoor studies were conducted. The relationship between OTC and air pollutants are especially relevant as building modifications (Krüger et al., 2011) and vegetation coverage (Fallmann et al., 2016) affect air movement within urban canyons and therefore, pollutant dispersion and temperature. Emergence of pollutant hotspots due to changes in urban geometry and greening may yield adverse impacts on pedestrian OTC, especially in dense urban landscapes.

We showed that the sensory urban environment has a tangible effect on individuals, it can encourage or discourage certain activities and affect perceptions, thus, it should be investigated in conjunction with thermal properties as these combined factors can have considerable stress on citizens.

2.3. How and to what degree can variations in urban design and vegetation evoke thermal pleasure and support dynamic thermal comfort?

Few studies explore the impact of various urban design attributes on alliesthesia in semi-outdoor and outdoor spaces that permeate the urban landscape. Thus, it is important to investigate the alliesthesial potential of semi-outdoor landscapes like raised building podiums, bus stop shelters and other urban forms beneficial for OTC such as parks and greenspaces.

For instance, measurement campaigns in Singapore showed diurnal PET range under elevated podiums was 1.5 °C, but above 10 °C for other exposed urban sites (Acero & Sun, 2020). PET under the elevated podium remained below 31.9 °C, which was within a thermally acceptable range based on another Singapore OTC study (Heng & Chow, 2019), while other exposed sites had seven or more hours of exposure above the threshold. A microclimate modelling simulation for hot, dry climate found that galleries, overhanging facades and vegetation were beneficial for reducing PET (Ali-Toudert & Mayer, 2007).

However, abovementioned studies did not explore human-involved OTC assessment and alliesthesial potential of these design elements. An experiment by Dzyuban et al. (2021) in a hot and dry climate found that bus stops with the presence of trees, landscaping and art design elements were perceived as more pleasant and thermally comfortable by public transit riders. Yu et al. (2016) explored the potential of temporally occupied spaces in Tianjin, China in evoking thermal pleasure after outdoor heat exposure. They identified acceptable ranges for cooling overshoots and duration of thermal alliesthesia. Another study of dynamic pedestrian experiences in a hot and dry climate showed that even small changes in PET influenced by variations in urban morphology and landscaping, resulted in overshoots in pleasure sensations (Dzyuban et al., 2022).

Greening urban landscapes proved beneficial in regulating microscale urban temperatures. An experiment on the effects of street vegetation on OTC indicated that street vegetation significantly reduced T_{mrt}. However, relationships between the aesthetic appreciation of greenery and OTC were inconclusive (Klemm et al., 2015). Recent studies also explored how layout and connectivity of greenspaces affect UHI and OTC. The theory of a patch corridor matrix suggests that greenspaces should be reasonably distributed across the urban environment. Zhu et al. (2020) posit that this network regulates microclimate and mitigates UHI. Size, shape, and configuration of greenspaces influence UHI intensity. Remote sensing imagery studies showed that relatively scattered and evenly distributed green spaces are more effective in mitigating UHI effects (Bao et al., 2016). Hence, urban planning and design guidelines indicate that medium- to large-sized greenspaces likely have significant cooling properties in urban landscapes. Studies directly connecting greenspace design to pedestrian thermal perceptions would help to inform landscape planning and design practices e.g., how diversified inner structure of greenspaces with windbreaks windward of leisure areas can influence OTC (Alcoforado et al., 2009).

2.4. What is the allisthesial potential among various population groups (pedestrians, outdoor workers, athletes etc.)?

Existing scholarships emphasise the importance of assessing personalised heat exposure. Most research agrees that OTC models perform poorly on an individual level (Nazarian & Lee, 2021), as the majority of studies have been focused on university students or office workers, excluding other more vulnerable and exposed groups. Research on occupational safety represents the smallest percentage of heat exposure assessments - an important lacuna to fill, especially with the highly variable nature of different outdoor occupations, and economic or behavioural motivations for overexposure to heat (Nazarian & Lee, 2021). Hastings et al. (2020) and Runkle et al. (2019) analysed OTC of outdoor workers, investigating their physiological responses while exposed to different outdoor conditions. These studies identified occupational workspaces that had increased exposure to heat (Hastings et al., 2020) and more vulnerable groups among the employees (Runkle et al., 2019). Subsequently, they recommended design alternatives to improve OTC and heat strain. Understanding the potential to relieve thermal discomfort while creating experiences of thermal pleasure can improve work conditions and increase productivity.

The widespread use of air conditioning precludes generalizations that urban populations in hot climates are more acclimated to heat. For instance, financial means and education indirectly impact thermal comfort as they determine one's ability to afford air-conditioning, influencing choices made to adopt heat mitigation strategies (Hass & Ellis, 2019). Evidence exists that outdoor workers and government employees have varied thermal comfort, exhibiting differences in acclimatization and expectations (Das, Das, & Mandal, 2020). Moreover, *meta*-analysis on heat mitigation strategies found an over-reliance on air conditioning and avoidance of high heat stress conditions may mute thermoregulatory benefits from heat acclimatization (Mishra et al., 2016; Alhadad et al., 2019; Runkle et al., 2019). However, as previously discussed, exposure to air-conditioned spaces can evoke thermal pleasure for individuals in transient conditions. Thus, more research on dynamic OTC is needed to understand where and when the discomfort is strongest and design strategies to alleviate it for different communities.

Agent-based modelling (ABM) is a promising method to simulate personalised dynamic thermal comfort. It is a bottom-up approach where the system models the immediate climatic variables around an agent and its adaptive behaviour. The agent 'thinks' for itself via a behaviour intention (BI) algorithm, where costs of each behaviour and activity is calculated, directing the agent's next course of action (Zhang et al., 2019). ABM shows potential as a predictive tool in modelling behavioural aspects of agents with individual physiological and lifestyle characteristics responding to thermal comfort and urban design variations within transient environments. Planners and landscape architects can thus base urban design off agent behaviour and preferences to various urban design features. However, the majority of current ABMs used for OTC analysis are based on steady-state OTC models (i.e., PET, UTCI) (Bruse, 2009; Maronga et al, 2019). Models also show limitations in predicting human behaviour (Melnikov et al., 2017). Nevertheless, there have been attempts to integrate dynamic outdoor thermal comfort into ABMs. For instance, Chen and Ng (2011) developed the PedNaTAS system that embedded the Pierce Two-Node Model for dynamic OTC assessment. Simulation incorporates three walking behaviours (social, proactive, and reactive) and is integrated within a Geographical Information Systems framework. The model can be used to create maps of overlaps between the frequency use and thermal comfort of outdoor urban areas (Chen and Ng, 2011). Embedding alliesthesia in an ABM thermal comfort module could improve the models' performance in complex outdoor settings. This could be done by integrating collected individual-level data into the models as well as using results of previous human involved studies.

3. Conclusions and future research directions

This study examined and clarified relationships between concepts typically used in OTC research. Recent climate impact assessments by the Intergovernmental Panel on Climate Change show that thermal discomfort in complex urban environments can lead to heightened heat risks and is expected to worsen in the future (Dodman et al. 2022). A common multidisciplinary framework and agreement on thermal comfort concepts would thus improve understanding and advance research in this important urban field. OTC studies often consider neutral conditions as optimal. This is far from reality in many cases as urban environments are complex and heterogeneous. Hence, achieving steady-state thermal conditions is highly improbable. Shifting the focus towards examining dynamic OTC in transient conditions potentially improves predictive power of OTC models, thus providing an opportunity for a deeper understanding of individual experiences. This conceptually challenges us to develop new approaches to capture the multidimensionality of thermal comfort. It is important to shift towards a holistic investigation of pedestrian routes and variations of conditions and user experience throughout their movement in the city. Moreover, we reported that confusion of concepts and differences in methodology can lead to significant differences in the results. Thus, research on dynamic OTC should focus on multidimensional approaches, involving both simulation and human-subject studies assessing their descriptive, affective, and preferential judgements.

Based on our review, we proposed research questions valuable to advance this field, exposed current gaps and suggested future research directions. Investigating these questions will support design and policy decisions addressing improvement of OTC in the context of increasing climate extremes and growing urbanisation. Since the same microclimate conditions will have a different effect on various individuals and population groups, it is important to understand the main users of a particular space to best accommodate their needs. Furthermore, incorporating diversity of microclimate conditions is essential for providing comfortable conditions to various population groups in urban landscapes. A certain degree of discomfort should be acceptable, and potentially beneficial, assuming that it can be ameliorated with more desirable conditions causing thermal pleasure. This approach allows a greater range of environmental conditions compared to what is currently deemed acceptable and optimal.

Declaration of Competing Interest

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

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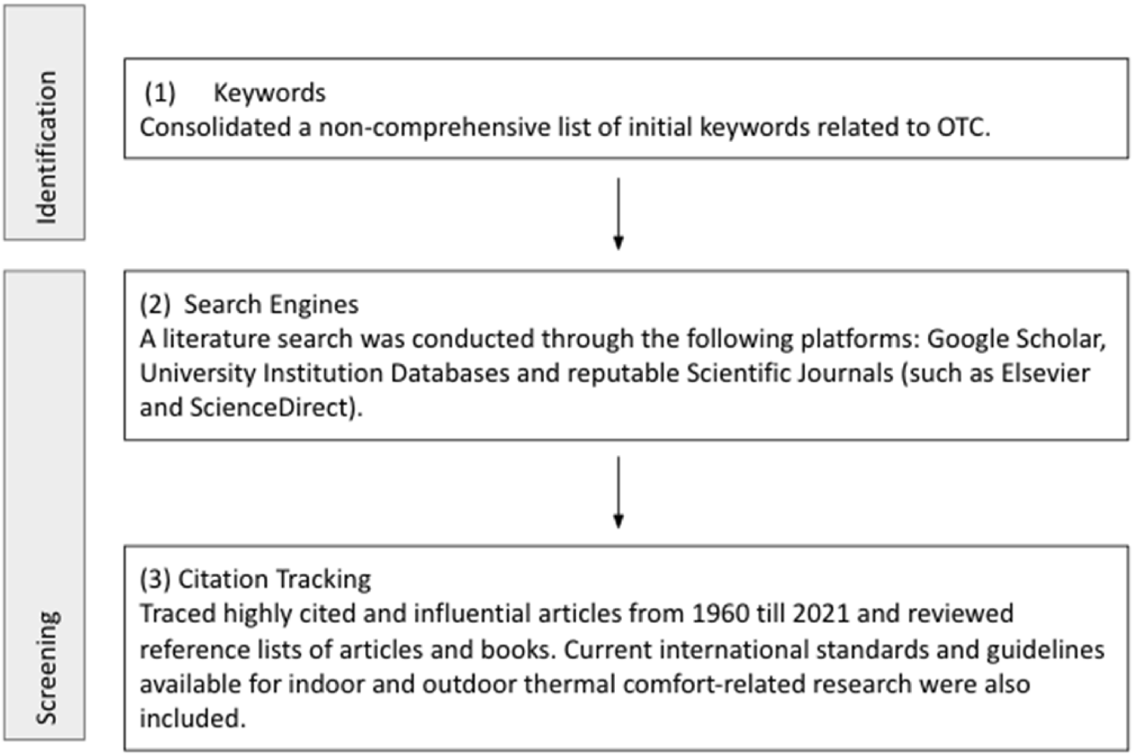
Appendix A. .

Review methodology adopted for review



(1) Keywords
Consolidated a non-comprehensive list of initial keywords related to OTC.

(2) Search Engines
A literature search was conducted through the following platforms: Google Scholar, University Institution Databases and reputable Scientific Journals (such as Elsevier and ScienceDirect).

(3) Citation Tracking
Traced highly cited and influential articles from 1960 till 2021 and reviewed reference lists of articles and books. Current international standards and guidelines available for indoor and outdoor thermal comfort-related research were also included.

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Appendix B. .

Keywords Searched.

List of keywords related to Outdoor Thermal Comfort
Thermal Sensation Vote
Thermal neutrality
Thermal acceptability
Thermal comfort
Thermal preference
Thermal expectation
Thermal satisfaction
Thermal sensation scale
Scales
Thermal pleasure
Alliesthesia
Non-steady state
Step-change environment
Skin temperature
Core temperature
Adaptive thermal comfort
Thermal comfort indices
Wearable sensors
Models

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2022.104496.

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