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REVIEW PAPER

Environmental, neuropsychological, and physiological factors in urban outdoor thermal comfort assessments: a systematic review

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Abstract

Excessive heat and thermal discomfort are growing threats for urban dwellers, severely affecting health and well-being. The complex interplay of urban structures, microclimates, and the diverse psychophysiological responses of individuals contribute to the complexity of Outdoor Thermal Comfort (OTC) studies. Prior literature has proposed various environmental and psychophysiological (i.e., human-centered) OTC assessment models. However, observational studies are necessary to understand OTC and to refine and validate these models. Yet, no guidelines exist for OTC observational study planning, making it challenging to collect environmental and psychophysiological OTC data following standardized practices. This paper presents a systematic review that summarizes the factors and parameters found in the participant-involved OTC observational studies described in 217 papers. Their geographical context, the environmental parameters studied, the meteorological instruments used, the biometric sensors, neuropsychological assessments, and thermal, environmental, and sensory surveys used, as well as the observational study planning strategies implemented in these papers were evaluated. Most papers used thermal surveys, while only 2% used sensory surveys. This review found that studies in continental and arid climates remain limited. Additionally, most studies targeted 18 to 60-year-old participants, while only 1.3% (3 papers) and 2.7% (6 papers) focused on children and the elderly. Only 5% of the observational studies used standardized neuropsychological assessments, all conducted in the last 10 years. Furthermore, physiological sensing to access cardiovascular, neurological, and dermatological functioning was only deployed in 18% of the studies. We outline knowledge gaps, identify research opportunities, and suggest potential frameworks for future observational study planning.

Keywords Psychophysiology · Human-centered · Surveys · Environmental comfort · Outdoor thermal comfort · Urban heat stress

Abbreviations

ASHRAE	ASHRAE 7-point pleasantness scale
BP	Blood pressure
DSB	Digit span backwards
ECG	Electrocardiogram
EDA	Electrodermal activity
EEG	Electroencephalogram
EV	Emotional valence
Globe	Globe temperature
GSR	Galvanic skin response
HRV	Heart rate variability
MRT	Mean radiant temperature
MMT	Mind map test
OTC	Outdoor thermal comfort
PANAS	Positive affect negative affect scale
POMS	Profile of mood state
PPG	Photoplethysmography
PRS	Perceived restorativeness scale
RESP	Respiration rate
RH	Relative humidity
ROS	Restorative outcome scale

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SC	Skin conductance
SD	Semantic differential scale
SpO2	Blood oxygen saturation
ST	Skin temperature
STAI-S	State-trait anxiety inventory
SVF	Sky view factor
SVS	Subjective vitality scale
TT	Typing test
UHI	Urban heat island

Introduction

With the combined effects of global warming and increasing urbanization, urban heat has become a public health concern. Each year, more than five million people worldwide die from heat (Lu and Cox 2021). Heat stress is a condition that occurs when the body is unable to regulate its temperature properly (Campbell et al. 2022). Heat-related illnesses, including heat exhaustion, heat cramps, and heat stroke, can result from heat stress (Rock and August 2019; Roghanchi et al. 2015). For example, a heatwave in Paris in 2019 caused 1500 excess deaths, with many more inhabitants suffering from severe health impacts that lasted long after the heatwave (Keith and Meerow 2021; Moini and Piran 2020; Rock and August 2019). Many municipalities now develop heat mitigation plans, advocating for green and blue infrastructures to provide shade, enhance evapotranspiration, and reduce the Urban Heat Island (UHI) (Görgen and Rossi-Schwarzenbeck 2021; Tengfei and Fong 2015) or surface painting to increase albedo and reduce the absorption of solar radiation by urban materials, consequently lowering heat emissivity (Andrés et al. 2021; Kalkstein et al. 2022; Schneider et al. 2023), amongst others.

The precursor of urban heat stress is thermal discomfort, which can be life-threatening when experienced by vulnerable groups such as the elderly, infants, and people with preexisting diseases such as diabetes, high blood pressure, obesity, and weight imbalances (Hsu et al. 2021; Li 2021). American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE-55) defines thermal comfort as "a psychological state that expresses satisfaction with the thermal environment and is assessed through subjective evaluations" (Ashrae 1992). Given the potential health threats that exposure to excessive heat poses, particularly for sensitive populations, providing thermally comfortable outdoor environments is crucial to promote public health, especially in dense urban areas where most of the global population live and where peak temperatures are more frequently observed (Haluza et al. 2014).

Factors influencing outdoor thermal comfort (OTC)

It is well known that exposure to micrometeorological stressors (e.g., direct solar radiation, high air temperature, and humidity) can lead to thermophysiological stress. However, meteorological factors only explain about 50% of an individual's OTC (Middel et al. 2016).

OTC is also driven by psychophysiological factors (where physiological body sensations are psychologically perceived and interpreted) (Klemm et al. 2015; Kobas et al. 2021), also called human-centered assessments (Raj et al 2011). When the temperature of the environment becomes greater than that of the skin, the body gains heat by both conduction and radiation (Yousef et al. 2022). Body temperature is then regulated and cooled by sweating and increased respiration (Lipczynska et al. 2020). Previous literature stated that individuals of different genders have temperature preferences that vary by up to 3 °C (Darlenski et al. 2022; Bar et al. 1969; Wang et al. 2022; Bastardot et al. 2019). Furthermore, underlying medical conditions such as mental illnesses, anxiety, or stress can also play a significant role in how individuals perceive thermal environments (Marques et al. 2021; Picton et al. 2020). Unusual sweating can be observed in people with mental health conditions, such as depression or anxiety, due to the release of adrenaline during episodes of increased anxiety (Bahar et al. 2016). This mental state triggers sweating, causing hyperhidrosis and resulting in the body's ineffectiveness to self-thermoregulate, making the individual prone to thermal discomfort (Wohlrab et al. 2023).

Multisensory interactions can also influence OTC. For example, excessive noise levels can affect psychological well-being and moderate OTC perception (Chen et al. 2022), whereby stress, annoyance, and distraction caused by noise, combined with heat, intensify the perception of discomfort (Sepehri et al. 2019). Loud noises can also stimulate the body's stress response (Bourikas et al. 2021), triggering physiological changes such as increased heart rate, blood pressure, and perspiration (Guan et al. 2020), which, in turn, affects thermal comfort perception and exacerbates the feeling of heat discomfort (Jin et al. 2020). Visual stimuli, such as a view from a window, also impact thermal perception (Ko et al. 2020). For example, a visually appealing view, such as a natural or green landscape, can positively influence thermal perception by creating a sense of psychological comfort, facilitating a perception that the environment is cooler and more comfortable (Chinazzo et al. 2021), even if the actual temperature remains the same. On the other hand, a visually unattractive or obstructed view leads to a perception of increased heat or discomfort (Lam et al. 2020). This effect has been explained by the visual stimuli and perceived expectation of control over visual inputs. Both cognitive distractions influence how individuals interpret and experience thermal conditions (Salamone et al. 2020).

Perceived control, which refers to an individual's belief in their ability to control their environmental conditions, also significantly influences OTC (Xu and Li 2021). For example, controlling clothing and moving to shaded outdoor spaces can impact comfort levels, potentially leading to higher comfort even in hot conditions (Zhou et al. 2023).

Figure 1 visually represents various environmental, physiological, and neuropsychological factors influencing OTC. The figure displays a person's experience of heat gain through radiation, convection, and conduction mediated by urban geometry, proximity to impervious surfaces (e.g., concrete pavements or asphalt roads), pervious surfaces (e.g., green areas or water bodies), or the exposure to direct sunlight or wind. Heat gain is further mediated by individual factors such as clothing, age, gender, ethnicity, body mass index, and personal preferences, leading to physiological responses, such as heart rate increases and sweating. These physiological responses contribute to personal thermal comfort, which can be further mediated by personal background surrounding multidimensional visual, auditory, or olfactory stimuli.

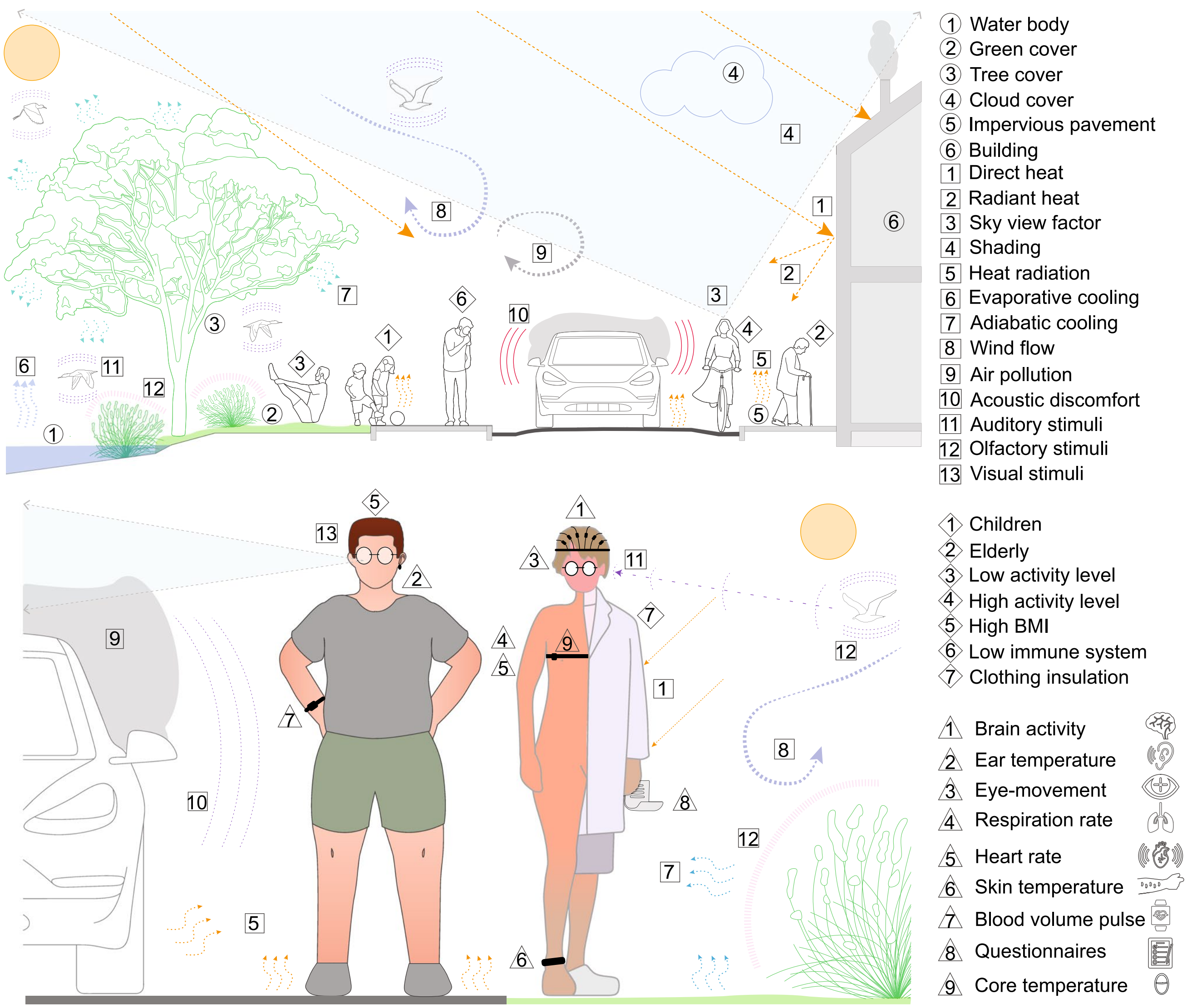

Fig. 1 Diagram of the multidimensional environmental, physiological, and neuropsychological aspects influencing OTC. Environmental elements present in urban spaces are listed with circles, the factors that influence OTC are listed with squares, the characteristics of the population affected by thermal discomfort are listed with diamonds, and the collected physiological data are listed as triangles

Challenges and advances in human-centered outdoor thermal comfort research

Data to perform OTC assessments can be collected through modeling and simulation approaches (synthetic data) or observational studies (observational study data) to inform thermal comfort indices (Li et al. 2022a, b, c; Matzarakis et al. 2016; Pantavou et al. 2020). Various literature reviews have focused on the description of these indices and have highlighted the challenges associated with incorporating subjective assessments to assess OTC (Dzyuban et al. 2022a; Lai et al. 2020; Nicol and Roaf 2017). Prior literature has repeatedly underlined the need for observational studies to collect environmental and psychophysiological data to better inform and validate these models and thermal indices (Coccolo et al. 2018; Middel et al. 2016; Dzyuban et al. 2022a). Recent review papers have also underlined the need for a framework to select the datasets to be captured and the observational study planning protocols to be implemented to perform human-centered observational studies to assess OTC (Cheung and Jim 2017; Elnabawi and Hamza 2020; Lai et al. 2020; Liu et al. 2021, 2020; Nikolopoulou et al. 2001; Shooshtarian et al. 2018).

With this motivation, this systematic review focuses on identifying the factors and parameters used for their thermal comfort assessments in prior human-centered OTC observational studies. However, this review is not an"input-data-focused systematic literature review, but it analyzes the factors/parameters used into thermal comfort assessments and indices.

To the best of the authors'knowledge, the last literature review examining OTC observational studies was conducted by Johansson et al. (2014). This review described the instruments and methods used to perform 26 observational studies and concluded that a standardized framework was necessary to perform OTC observational studies. In the last decade, with increased recognition of the need for psychophysiological OTC assessments and advances in physiological sensing technologies, several studies on human-centered OTC observational study assessments have been conducted (Berto 2014; Kumar and Sharma 2020; Mansi et al. 2021; Persiani et al. 2021; Piselli et al. 2018). Reviewing this literature is necessary to evaluate and refine data collection and observational study practices for human-centered OTC assessments, hence the focus of this systematic review.

Materials and methods for systematic review

A literature search was developed through the Abstract and Citation database Scopus, Web of Science (WoS), and Pubmed. Furthermore, Google Scholar was used to identify relevant grey literature of interest and articles referenced in the reviewed articles under the framework of this work. Version 2020 of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Page et al. 2021a) was adopted for a multi-step literature search and review. The first step involved the identification of relevant keywords and search queries (see Sect. 2.1). The second step was the definition of the exclusion criteria (Sect. 2.2), and the third step was to perform the systematic review, which resulted in 217 papers for discussion in Table B.6. This review focused on identifying the factors and parameters used for their thermal comfort assessments. Another publication focusing on thermal comfort indices will be prepared in the future.

Search strategy & selection criteria

A literature search was conducted using two different search queries described below (Fig. 2). The two search methods focused on OTC observational studies, including papers focused on environmental measures, neuropsychological assessments, and physiological measures. The common keywords ("Outdoor"AND"Therm*"AND"Comfor*") were combined with environmental and monitoring-related terms common to both methods: ("Environmen*"OR"Weather*"OR"Climat*"OR"Microclimat*"OR"Micrometeorolog*"OR"Biometeorolog*"OR"Temperat*"OR"Heat*").

Method 1 – Environmental Measures and Neuropsychological Assessments:

These common terms were combined with neuropsychological-specific keywords: (“Psycholog*” OR “Behavi*” OR “Percep*” OR “Questionnaire*” OR “Survey*” OR “Interview*” OR “Observ*” OR"Subjectiv*"OR"Sensation*").

Results: 2243 papers from Scopus, 2259 from Web of Science, and 258 from PubMed.

Method 2 – Environmental and Physiological Measures:

The common terms were combined with physiological-specific keywords: (“Physio*” OR “Human*” OR"Sensor"OR"Instrument*"OR"Measure*"OR “Experiment*” OR “Device*” OR “Smart*” OR “Watch*” OR"Monitor*").

Results: 444 papers from Scopus, 3139 from Web of Science, and 382 from PubMed.

Hence, the search yielded 8725 papers (2622 from Scopus, 5398 from Web of Science, and 595 from PubMed) with 4111 duplicates. The unique 4614 papers were passed through the abstract and title screening following the PRISMA-compliant exclusion criteria (Page et al. 2021b, 2021a) and rationale described in Sect. 2.2. Of 4614 papers with abstract and title screening, 4164 papers were excluded, and the remaining 447 papers were retrieved. Of these 447 papers, 74 were not retrieved (they were neither available on open-access platforms nor indexed in Scopus or other academic repositories, including ResearchGate or Google Scholar), 156 were excluded through full-text screening, and the remaining 217 were included and listed in Table B.6.

The literature search is limited to the period from January 1, 2001 to March 21, 2024. Publications after this date were

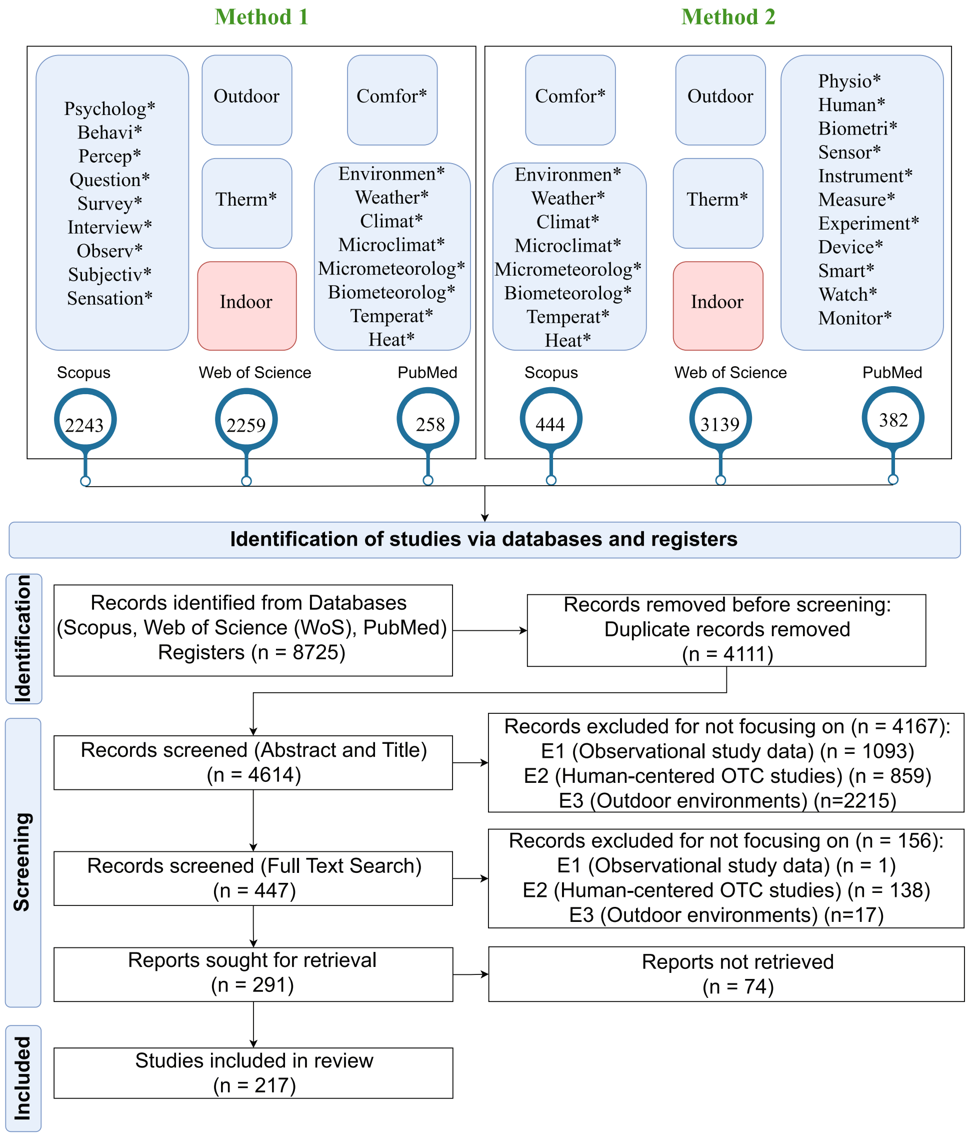

Fig. 2 Search strategy and screening process for including and excluding papers

not reviewed. Also, studies written in languages other than English were not reviewed.

Exclusion criteria

Exclusion criteria #1 (E1)—Not focused on observational study data collection.

A total of 1093 papers from the abstract and title search and one from the full-text search were excluded for not reporting observational studies for OTC assessment.

Exclusion criteria #2 (E2) – Not focused on human-centered OTC studies.

Papers that did not use participant surveys, standardized neuropsychological assessments, or physiological measures to evaluate OTC were excluded, totaling 859 in the abstract and title search and 138 in the full-text search.

Exclusion criteria #3 (E3): Not focused on outdoor environments.

Studies exclusively examining indoor environments were excluded, with 2215 papers removed at the abstract and title search stage and 17 at the full-text stage. Only studies providing a comparative analysis of indoor and outdoor environments were retained.

Exclusion criteria #4 (E4): Article not retrievable.

A total of 74 papers were excluded during the full-text search as they were not accessible through open-access platforms or indexed in Scopus, ResearchGate, Google Scholar, or other academic repositories.

In Fig. 2, the Boolean operator"OR"was applied to combine keywords within each blue circle, while"AND"was used to link different blue circle categories. The"NOT"operator (red circle) was used to exclude studies focused on indoor.

Results of literature review

A parallel coordinate plot was created to visualize the selected 217 papers (see Fig. 3). The plot includes columns for the year of publication (column 1), climate type in which the observational study was done (column 2), urban or park study area type (column 3), environmental parameters (column 4), Thermal and sensory survey with participants (column 5), neuropsychological assessments (column 6), physiological parameters (column 7), participant count (column 8), and type of study (longitudinal or cross-sectional) (column 9).

As shown in column 1, the number of publications discussing observational studies for human-centered OTC assessments has shown an increasing trend over the years. This trend is driven by the increasing availability of accessible and affordable environmental and psychophysiological sensing technologies, along with the growing interest in personal health monitoring through smart devices such as smartwatches and headbands (Coulby et al. 2020; Henriksen et al. 2018).

This trend is further explored in Fig. 3, highlighting patterns in the existing literature, such as the commonly observed environmental parameters or the most frequently used physiological measures and neuropsychological assessments in observational studies.

The following distinction has been made between neuropsychological assessments, thermal surveys, and sensory surveys: 1) Neuropsychological assessments are standardized tools for collecting data on the state of participants based on peer-reviewed research in neuropsychological sciences focused on measuring comfort and mental well-being (Das et al. 2020; De Los Reyes et al. 2019). 2) Thermal surveys are questionnaires focusing solely on assessing thermal well-being, not psychological well-being (Adrian et al. 2008; Velt and Daanen 2017; Zhao et al. 2021). 3) Sensory surveys are questionnaires focused on capturing other environmental sensorial dimensions in relation to individual comfort, such as fragrance, acoustic, and vision (Chang et al. 2023; Dong et al. 2021; Hu et al. 2022; Lau and Choi 2021). This review does not focus on OTC modeling literature, simulation works, or observational studies without participant monitoring.

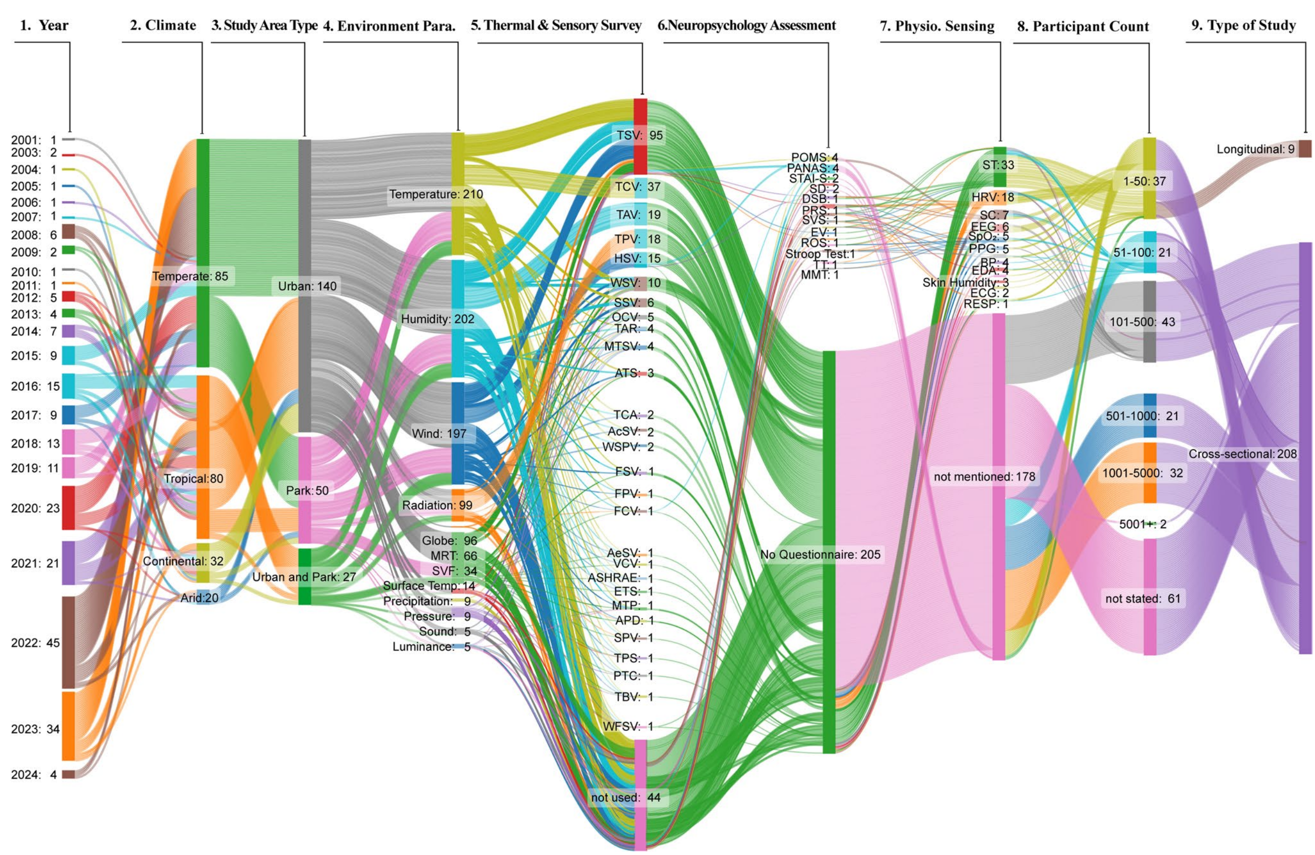

Fig. 3 Parallel plot representing the gathered 217 papers

Climate of the observational study site

Column 2 of Fig. 3 represents the climate of the location where OTC observational studies were conducted. The studies span a range of Köppen climate types (Beck et al. 2018), which include temperate (85), tropical (80), continental (32), and arid (20). Papers have primarily focused on observational studies in temperate climate conditions, but the number of studies on tropical climates has increased over time.

Temperate climates are represented by 85 studies developed in different countries which include: Cyprus (1), Chile (2), South Korea (4), Italy (5), China (35), Japan (5), Spain (4), Portugal (4), Netherlands (6), Australia (5), Greece (3), New Zealand (1), USA (3), UK (2), England (2), Germany (3), Tropical climate are represented by 80 studies, developed in different countries which include: China (31), Brazil (5), India (5), Singapore (10), Taiwan (7), Indonesia (2), Malaysia (6), Ecuador (2), Hong Kong (7), Barbados and Tobago (1), Australia (1), Colombia (1), Sri Lanka (1), Cuba (1). Continental climates are represented by 32 studies developed in different countries, which include China (14), Canada (3), Czech Republic (1), Hungary (4), Turkey (1), Iran (1), Poland (1), Sweden (5), Serbia (2), and Arid climate are represented by 20 studies, developed in different countries which include: Iran (1), Algeria (5), Egypt (2), USA (5), Turkey (2), Jordan (1), Argentina (1), Brazil (1), Israel (1), Australia (1).

For some of these countries, achieving OTC can be more challenging, given that thermal discomfort is intensified by higher levels of humidity, solar radiation, and greater temperature variations between day and night (Dasari et al. 2021; Yasmeen and Liu 2019). Column 3 of Fig. 3 represents the site where the observational studies were performed as urban or green spaces (such as parks with trees and plants). From the 217 papers collected, 140 studies were conducted in built-up areas, 50 in green spaces, and 27 in urban and green spaces.

Environmental parameters

Column 4 of Fig. 3 represents the environmental parameters measured. Weather and climate conditions determine thermal comfort, and the importance of environmental parameters varies depending on the climatic zone (Antypov et al. 2022; Chea et al. 2021; Kamchen et al. 2018). For example, in hot and arid climates, solar radiation can cause excessive sweating, dehydration, and increased risk of heat exhaustion or heat stroke, making it a crucial OTC parameter to capture (Gachkar et al. 2021; Ma et al. 2021; Shawesh and Mohamed 2021; Tian et al. 2022).

Air temperature, which directly affects individual heat balance and thermal perception, was measured in 162 of 217 papers using sensors on site. Relative humidity and wind speed & direction, which also affect thermal comfort through heat transfer between the body and the environment, were measured on-site in 158 and 161 papers, respectively, out of the 217 papers.

Prior literature highlights the importance of capturing radiant heat exchanges between the human body and surrounding surfaces. This data collection involves documenting the Mean Radiant Temperature (MRT), the weighted average temperature of all the surfaces surrounding a person, influencing radiant heat exchange (Guo et al. 2020). Measured on site in 66 of the 217 papers, MRT is influenced by the solar radiation absorbed by impervious surfaces such as pavements or building facades (Fröhlich and Matzarakis 2018; Wang and Akbari 2014), provides insights into the heating and cooling dynamics associated with surfaces around pedestrians in urban settings (Li et al. 2022a, b, c). For example, Dzyuban et al. (2022b) used the mobile mean radiant temperature cart MaRTy for detailed micrometeorological observations, including air temperature measurements, relative humidity, and radiation flux densities at the pedestrian level to acquire MRT.

The Sky View Factor (SVF) quantifies the amount of sky on a hemisphere visible from the ground (Bernard et al. 2018). Low SVF indicates urban areas with dense construction where the sky is less visible due to obstructions like buildings and trees. This reduced sky visibility can lead to several effects: it diminishes direct sunlight reaching the ground, decreases solar heat gain during the day, decreases MRT, and limits wind movement. Low SVFs decrease radiative cooling at night as the heat retained by buildings is not efficiently emitted back, resulting in increased MRT over time (Inavonna et al. 2018). For example, in arid and desert climates, clear sky and intense sun contribute to significant daytime heating, for which low SVF accounts for shading and reduced MRT (Hartabela et al. 2021; Middel et al. 2021; Paramita and Fukuda 2014). Hence, the importance of documenting the SVF is widely accepted in literature, and it was measured on-site in 34 of the 217 papers studied. Surface temperature and luminance were measured on-site in 14 & 5 papers.

Vapor pressure and precipitation were collected from a weather station in nine, and nine of the 217 papers (respectively), both affecting the thermal environment and individuals'thermal perception. The sound level was collected on-site in 5 papers. For example, a paper reported that noise levels influence thermal comfort perception in warm environments (Cureau et al. 2022).

Table 1 presents these environmental parameters and the number of studies that collected them. Various instruments were used to capture these meteorological observations, which have been listed in Table 2, where each provides information about the measured environmental parameters, the instrument type, the instrument's least count (or smallest

Table 1 Standardized neuropsychological assessments as cited in the literature

Sr	Neuropsychological assessments	Questionnaire reference	Type	From the 217 Papers
1	Profile of Mood State (POMS)	McNair et al. (1971)	Subjective neuro-psychological assessments	(Yoshida et al. 2015), (Elsadek et al. 2019c), (Lin et al. 2019)
2	Positive Affect Negative Affect Scale (PANAS)	Watson et al. (1988)		(Peng et al. 2019), (Chang et al. 2023), (Zhang et al. 2021), (Niu et al. 2023)
3	Semantic differential scale (SD)	Osgood and Tannenbaum (1955)		(Elsadek et al. 2019b; Yoshida et al. 2015)
4	State-Trait Anxiety Inventory (STAI-S)	Spielberger et al. (1983)		(Elsadek et al. 2019b), (Lin et al. 2019)
5	Perceived Restorativeness Scale (PRS)	Hartig et al. (1997)		(Huang et al. 2021)
6	Emotional Valence (EV)	Anderson (1996)		(Xi et al. 2023)
7	Restorative Outcome Scale (ROS)	Yusli et al. (2021)		(Elsadek et al. 2019b)
8	Subjective Vitality Scale (SVS)	Ryan and Frederick (1997)		(Elsadek et al. 2019b)
9	Digit Span Backwards (DSB)	Wechsler (1940)	Objective neuro-psychological assessments	(Chen et al. 2022)
10	Stroop test	Stroop (1935)		(Chen et al. 2022)
11	Mind Map Test (MMT)	Buzan (1993)		(Chen et al. 2022)
12	Typing Test (TT)	Dvorak et al. (1936)		(Chen et al. 2022)

unit of measurement), and the number of papers where it has been used in the collected literature.

In most observational studies reviewed (in 199 of 217 papers), environmental sensing was deployed in a static frame of reference where the environmental sensing device was stationary and continually captured meteorological conditions. Of 217 papers, 48 relied on data supplemented from a nearby weather station, as shown in Table 1, which does not represent local micrometeorological conditions experienced by participants on site. Only 19 papers used mobile environmental sensing, with participants wearing environmental sensors while walking or cycling. In an observational study by (Klemm et al. 2015), cyclists were equipped with a shielded thermometer, a humidity sensor, a 2-dimensional sonic anemometer, and radiation sensors to measure solar radiation and thermal infrared radiation exchange. Most observational studies do not consider mobility and dynamic changes due to the movement of individuals.

Thermal and sensory surveys

Column 5 of Fig. 3 represents the thermal surveys assessed in the collected papers. Thermal surveys aim to evaluate how temperature, humidity, wind, and solar radiation affect the human experience of comfort (Adrian et al. 2008; ASHRAE Standard 55, 2020; Bedford 1936; Gagge et al. 1967; Givoni 1963; Humphreys 1976; Liu and Jordan 1960; Velt and Daanen 2017; Zhao et al. 2021). Thermal surveys were used in 174 papers (80%). Thermal Sensation Vote (TSV), Thermal Comfort Vote (TCV), Mean Thermal Sensation Votes (MTSV), and Actual Thermal Sensation (ATS) were used in 132 papers. Thermal Acceptability Vote (TAV) and Thermal Acceptability Range (TAR) were used in 23 papers. Thermal Preference Vote (TPV) and Momentary Thermal Preference (MTP) were used in 19 papers. Thermal surveys were utilized in 24 papers (11%) to assess environmental factors, namely humidity, wind, and sunlight, that affect human comfort perception. (Jin et al. 2012; Vokac et al. 1976). The Humidity Sensation Vote (HSV), Wind Sensation Vote (WSV), and Sun Sensation Vote (SSV) were used in 17 papers, and the Wind Speed Preference Vote (WSPV), and Sunlight Preference Vote (SPV) were used in 7 papers. The thermal surveys used in the gathered literature have been listed in Table 3.

Sensory surveys, which were used in 5 papers (2%), aim to evaluate how other environmental sensorial dimensions, such as fragrance, sound, or views, influence the human perception of comfort (Chang et al. 2023; Dong et al. 2021; Hu et al. 2022; Lau and Choi 2021). Surveys focusing on fragrance sensation include the Fragrance Sensation Vote (FSV), Fragrance Pleasantness Vote (FPV), and Fragrance Comfort Vote (FCV). Surveys focusing on acoustic comfort include the Mean Acoustic Vote (AcSV), and surveys focusing on visual comfort include the Visual Comfort Vote (VCV) and the Aesthetic Sensation Vote (AeSV). Sensory surveys used in the gathered literature have been listed in Table 3.

Thermal indices estimate thermal comfort based on environmental parameters including air temperature, relative humidity, wind speed, and mean radiant temperature, with certain indices also incorporating metabolic rate and clothing insulation to provide a more comprehensive assessment of thermal comfort (Blazejczyk et al. 2012; de Dear and Brager 1998; Fanger 1970; Höppe 1999; Jendritzky et al. 2012). Due to word limit constraints, a summary of relevant indices has been included in the supplementary material (Table B.4). Given the complexity of this topic, we plan to conduct a follow-up study explicitly analyzing

Table 2 Physiological sensing parameters and their cited papers in selected literature

Parameter	Description	Physiological measure	How it relates to thermal stress	No of paper
Skin Temperature (ST)	The temperature of the skin	Monitoring stress and arousal levels	Skin temperature can change in response to thermal stress. Higher skin temperature can indicate increased heat stress and discomfort (Hastings et al. 2020)	33
Heart Rate Variability (HRV)	The variation in time between consecutive heartbeats	Monitoring stress levels	HRV can indicate autonomic response to thermal stress. Changes in HRV reflect the body's adaptation to thermal conditions and perceived comfort (Huang et al. 2010)	18
Skin Conductance (SC)	Reflects sweat gland activity	Tracks emotional arousal, stress response	Reflects thermoregulatory sweating response (Hayashi 1968)	7
Electroencephalogram (EEG)	Measures the electrical activity of the brain	Evaluating cognitive performance and attention levels	Thermal stress can impact cognitive function and attention. EEG can capture changes in brain activity due to thermal stress. (Lee et al. 2015; MacLeod et al. 2018; Taylor et al. 2016)	6
Photoplethysmography (PPG)	Measures blood volume changes	Monitors heart rate, stress levels	Can be influenced by changes in body temperature (Bain and Jay 2011)	5
Blood Oxygen Saturation (SpO2)	Indicates oxygen levels in the blood	Indicates respiratory and circulatory health	It is affected by respiratory changes due to heat stress (Girard et al. 2021)	5
Electrodermal Activity (EDA)	Measures the electrical conductance of the skin	Measure changes in emotional state	EDA can reflect physiological changes from thermal stress, such as increased sweating or arousal levels. Higher EDA indicates higher thermal discomfort (Kobas et al. 2021)	4
Blood Pressure (BP)	The pressure of blood in the arteries	Monitoring heart function	Blood pressure can increase in response to thermal stress, reflecting the body's physiological response to maintain thermal balance (Barnes and Charkoudian 2021; Cui et al. 2010; Padilha et al. 2022)	4
Skin Humidity	Amount of moisture in the air	Affects comfort, respiratory conditions	It affects the body's ability to cool through evaporation (Zuo et al. 2021)	3
Electrocardiogram (ECG)	Measures the electrical activity of the heart	Monitoring heart function	ECG provides information about heart health and function. It can indicate the impact of thermal stress on heart rate and rhythm (Carter et al. 2005; Mimish 2012; Wilson and Crandall 2011)	2
Respiration Rate (RESP)	Counts breaths per minute	Indicates stress, relaxation, and metabolic rate	Increases as the body attempts to release heat (Saxton 1981)	1

Table 3 Observational study strategy and population groups

Age	No. of studies	Climate	Study population					Longitudinal	Cross-sectional
			Min	Max	Mean	SD	Total		
< 18	3	Continental (1) Tropical (2)	9	296	121	153	365	0	3
18–60	112	Temperate (50) Tropical (38) Continental (16) Arid (8)	1	7851	597	1628	64575	7	105
> 60	6	Temperate (3) Tropical (2) Continental (1)	45	1417	442	450	2654	1	5
Age Not Stated	96	Arid (12) Continental (14) Temperate (32) Tropical (38)						1	95

how various thermal indices align with physiological and neuropsychological measurements.

From the 217 papers reviewed, 174 used thermal surveys, 5 used sensory surveys, and 38 did not use thermal or sensory surveys.

Neuropsychological assessments

Column 6 of Fig. 3 represents the standardized subjective and objective neuropsychological assessments used in the reviewed papers. Of the 217 papers selected, ten only used subjective neuropsychological assessments, and one used objective neuropsychological assessments.

Subjective neuropsychological assessments rely on individuals'self-reported perceptions and experiences to assess their mental states and behaviors (Das et al. 2020; De Los Reyes et al. 2019). Subjective and objective neuropsychological assessments are discussed further in this section.

Four papers used the Profile of Mood States (POMS) questionnaire. POMS assesses mood states such as tension, depression, anger, vigor, fatigue, and confusion influenced by thermal conditions (McNair et al. 1971). Thermal discomfort influences an individual's mood and state of mind (Kim et al. 2023; Pearlmutter et al. 2014). Mood states are amongst the first biological responders to stress, including thermal distress, which is why the POMS score is important for assessing OTC (Turhan et al. 2023). For example, lower POMS tension-anxiety scores were reported when walking on streets covered with trees (Elsadek et al. 2019c; Yoshida et al. 2015), concluding that the presence of nature reduced tension-anxiety, improved mood, and increased the perception of comfort even though physically the OTC remained the same (Elsadek et al. 2019c; Lin et al. 2019).

Four papers used the Positive and Negative Affect Schedule (PANAS) questionnaire. PANAS measures positive and negative emotional states of mind that can influence the perception of OTC (Watson et al. 1988). For example, a study using the PANAS questionnaire found that in summer, higher temperatures decreased Positive Affect (PA) scores, indicating a decline in emotional well-being due to increased thermal discomfort (Zhang et al. 2021). Another study using the PANAS questionnaire showed a greater influence of green spaces on positive emotions irrespective of thermal discomfort due to summer (Niu et al. 2023).

Two papers used the Perceived Restorativeness Scale (PRS) questionnaire. PRS assesses the perceived restorative quality (i.e., the ability to replenish cognitive and emotional resources (Pasanen et al. 2018; Scopelliti et al. 2019)) of the outdoor environment (Hartig et al. 1997). Huang et al. (2021) and Nakata et al. (2021) confirmed that restoration from thermal stress was higher in environments with plants and water bodies.

Three papers used the State-Trait Anxiety Inventory (STAI-S) questionnaire. STAI-S measures state (temporary) and trait (general) anxiety, which could be inherited due to thermal discomfort (Spielberger et al. 1983). Thermal stress has been reported to induce anxiety, which is evidenced by an increase in STAI-S scores, indicating higher perceived anxiety levels (Mauriz et al. 2020). Elsadek et al. (2019c) showed that STAI-S questionnaire scores measuring current anxiety were significantly lower after walking along roads with higher tree coverage, irrespective of thermal conditions. They found an increase in anxiety levels when walking on the control road without trees.

One paper used the Subjective Vitality Scale (SVS) questionnaire. SVS measures the feeling of energy and vitality, which is also influenced by OTC (Ryan and Frederick 1997). Previous research has shown that physiological stress due to changes in thermal condition affects the subjective vitality of participants, which was assessed using the SVS questionnaire (Frederick and Ryan 2023; Goldbeck et al. 2019). E.g., Elsadek et al. (2019c) also used the SVS questionnaire and found an increase in the subjective vitality of participants when walking along roads with green spaces and a lower PET, compared to roads with no green spaces and a higher PET.

Two papers used the Semantic Differential (SD) questionnaire. SD evaluates the connotative meaning of objects, events, and concepts present in an outdoor environment, which has been shown to influence the perception of OTC (Osgood and Tannenbaum 1955). Yoshida et al. (2015) found that participants reported a greater sense of relaxation and reduction of thermal stress when viewing nature and sitting under trees, as indicated by a higher positive rating on the SD scale.

One paper used the Emotional Valence (EV) questionnaire. EV measures the positive or negative value associated with a stimulus in an outdoor environment (Anderson 1996). Xi et al. (2023) noticed an agreement between EV and TCV surveys, stating that a good mood (measured using EV) improved the perception of thermal comfort (measured using TCV).

One paper used the Restorative Outcome Scale (ROS) questionnaire. ROS measures the actual restorative outcome experienced by the participants in the outdoor environment (Yusli et al. 2021). Elsadek et al. (2019c) reported that under similar PET levels and in the small shading effect of certain trees, participants still experienced psychological restoration, which improved OTC.

The collected literature using subjective neuropsychological assessments showed that the thermal conditions affected the participant's assessment scores. However, these assessments agreed that green spaces with trees improved the subjective state of participants.

On the other hand, objective neuropsychological assessments rely on cognitive tasks to assess mental states and behaviors (Grassini and Laumann 2020; Loevinger 1957). The selected literature includes objective neuropsychological assessments; the Digit Span Backwards (DSB) test, Stroop test, Mind Map Test (MMT), and the Typing Test (TT). DSB measures working memory capacity (Wechsler 1940), Stroop Test assesses cognitive control and attentional capacity (Stroop 1935), MMT measures cognitive mapping and organizational skills (Buzan 1993), and TT evaluates cognitive attention while measuring typing speed and accuracy (Dvorak et al. 1936). Chang et al. (2023) used all four of these objective neuropsychological assessments and concluded that the thermal environment consistently impacted cognitive performance, memory capacity, creativity & processing speed. At the same time, observing nature improved all these cognitive resources even though thermal conditions remained the same.

The standardized neuropsychological assessments used in the gathered papers, along with their questionnaire reference of publication, the type of questionnaire, and the papers where they were used, have been included in Table 1.

Physiological sensing

Column 7 of Fig. 3 represents the physiological sensing used in reviewed papers.

Physiological sensing was performed in 18% (40 out of 217) papers. Physiological sensing refers to measuring various biometric parameters, such as skin temperature, blood pressure, and heart rate, which can provide insights into how the body responds to OTC changes (Khan and Azari 2021; Morresi et al. 2021).

For example, as temperature increases, the body tries to regulate internal temperature by increasing blood flow to the skin, which can increase Skin Temperature (ST) (Inavonna et al. 2018).

Infrared (no-contact) and thermocouple (on-contact) thermometers were used to measure ST in 33 papers in the collected literature. For example, in an observational study by Vanos et al. (2010), a wrist-worn thermocouple measured the ST of 12 participants while cycling. The study concluded that different activities that involve physical exercise change the heat emitted, causing changes in the comfort experienced by participants.

Skin Conductance (SC) measures the skin's electrical conductance, which varies with changes in sweat gland activity and is used in 7 out of 217 papers. Measuring SC can help understand emotional arousal in participants, which can be related to how (comfortable or anxious) they feel in a given environment (Farnsworth 2019).

Electrodermal Activity (EDA), used in 4 out of 217 papers, measures the variation of the electrical properties of the skin in response to sweat secretion (Boucsein 2012).

Photoplethysmography (PPG), used in 5 of 217 papers, is a non-invasive optical technique used to detect volumetric changes in blood circulation within the microvascular bed of tissue, which will help in signaling when thermal discomfort leads to an increase in the rate of blood flow volume of skin (Kamshilin et al. 2011).

Changes in Blood Pressure (BP) and Heart Rate Variability (HRV) were used in 4 and 18 of 217 papers, respectively. HRV can also occur in response to changes in thermal comfort and their neuropsychological state. Therefore, monitoring can help identify the stress or discomfort experienced by individuals in different thermal environments and provides valuable information for designing urban spaces that promote comfort and well-being (Rahma et al. 2022).

Electroencephalogram (EEG), used in 6 of 217 papers, is a neurophysiological measurement that records electrical activity from the brain to provide insights into cognitive processes and brain functioning (Light et al. 2010). The details of all physiological parameters captured in the reviewed literature are presented in Table 2. The complete list of instruments is listed in Table B.5. A qualitative illustration of the human-centered sensors is also included in Fig. 1. Fig. A.1 in the appendix shows a compilation of all the environmental parameters, thermal and sensory surveys, neuropsychological assessments, and physiological measures collected in the selected papers.

Observational study planning

Columns 8 and 9 of Fig. 3 represent the participant count and type of study done in the reviewed papers. Of the 217 papers, 208 were cross-sectional studies, and 9 were longitudinal studies.

Cross-sectional studies generally focused on a large cohort of participants, taking 5 to 15 min per participant within the observational study (Portnova et al. 2020; Pye et al. 2016). For example, a study by Lau and Choi (2021), gathered 1842 random participants who were provided with thermal and sensory surveys. They reported that dissatisfaction with the environmental aesthetics increased the perception of thermal discomfort. Lehnert et al. (2021b) worked with 1522 random participants to identify thermal discomfort hotspots in urban areas. They found that the resident-identified hotspots differed from those based on surface temperature measurements, indicating a need for further investigation. Similarly, Tian et al. (2022), in a study with 1772 random participants, concluded that thermal perceptions in their study area were influenced by physical, individual, social, and psychological factors, and further studies assessing these factors are needed. In these studies, a large number of participants were necessary to ensure a fair distribution of respondents for data collection and statistically coherent results to account for variations in thermal conditions within their study areas (Lehnert et al. 2021a, b; Tian et al. 2022; Lau and Choi (2021).

Conversely, longitudinal studies generally focused on a specific population cluster to document their OTC preferences over time (Jin et al. 2019; Zhang et al. 2019). Zheng et al. (2023) conducted a longitudinal study with two assessments on 44 elderly individuals aged 60 and above from July to August 2019 and 2021. They concluded that basal metabolic rate, cardiac output, and sensitivity to environmental factors decreased with age. On the other hand, Vanos et al. (2010) concentrated on a younger demographic, recruiting 12 participants aged 19 to 23 for a 30-min observational study involving exercise (running and cycling) in four different periods. They concluded that core temperature is crucial in human thermoregulation, significantly influencing sweat rate and skin temperature. Longitudinal studies have also been performed while focusing only on one gender, such as Li et al. (2022a, b, c), who recruited 10 male participants aged 22 to 30 years for their study. They conducted observational studies annually from 2016 to 2017 and concluded that the participants had an increased pulse rate in hot climates (32 °C), while in cold climates (16 °C), they exhibited lower blood pressure.

Table 3 displays the observational studies developed within the selected literature per age range. The climatic zones of these papers are also studied, as well as the type of observational study, whether longitudinal or cross-sectional, and the number of participants tested.

Discussion

Environmental urban OTC assessment

Prior literature has extensively documented temperature, humidity, and wind when characterizing the environmental conditions of an urban site. The importance of documenting globe temperature, MRT, and SVF has also been repeatedly addressed. However, these were reported only in 88, 66, and 34 of the 217 papers, respectively, using sensor and weather station data.

Further, many papers rely on the RayMan model to derive MRT using globe temperature readings rather than measuring MRT on the field. Hence, the understanding of long and shortwave radiation in the local micrometeorology and their impact on OTC, while regarded as highly important in prior literature, remains limited in most human-centered OTC observational studies. Measuring MRT remains costly and requires expensive sensors, which are often difficult to operate (Kántor and Unger 2011). As described by Krüger et al. (2014), this has led researchers to exclude MRT measurements from their studies. Given the high cost of integral radiation measurement, several papers in prior literature have proposed to use models such as RayMan (Matzarakis et al. 2007). MRT has also been quantified using low-cost environmental monitoring devices such as the PLEMS (Krüger et al. 2024), the MaRTiny IoT device (Kulkarni et al. 2022), globe thermometers (Vanos et al. 2021), cylindrical radiation thermometers (CRTs) (Rykaczewski et al. 2024), and the SMART sensor (Aviv et al. 2021; Houchois et al. 2019).

Furthermore, prior literature has highlighted environmental monitoring considerations specific to climatic and geographic conditions. For example, in coastal areas, parameters such as humidity levels are more critical due to the proximity to large bodies of water. The presence of water bodies increases the moisture content in the air, leading to higher humidity levels, which make individuals feel hotter and more uncomfortable, even at lower temperatures (Cheng et al. 2022). In regions prone to heavy rainfall or tropical storms, precipitation intensity, duration, and frequency are critical environmental parameters to monitor as they impact peak surface temperature (Ngo et al. 2022). In dry/arid regions, air temperature and solar radiation change significantly from day to night and must be monitored along with wind speed (Bertoldi et al. 2007).

In addition to monitoring environmental parameters, it is important to consider the environmental sensing strategy. However, the discussion on environmental data collection during OTC observational studies explicitly tailored to local climatic conditions remains underexplored. There is a lack of research specifying the parameters to be measured and the optimal locations for their measurement. Moreover, whether OTC measurements should be conducted using stationary or mobile instruments remains unclear. For example, 91% of the observational studies used stationary field setups to monitor local environmental conditions. Using stationary stations provides the advantage that participants are not required to carry environmental sensors as they navigate the urban environment, and the data can be more easily locally stored and sensing instruments calibrated (Geng et al. 2022; Zhang et al. 2023). However, stationary weather stations only provide data for a limited extent, which can leave undetected thermal hotspots. Enabling data collection while individuals are on the move (e.g., by the individuals carrying sensing kits within backpacks or trays (Gallinelli 2017) can allow for documentation of citizen environmental stress exposure across different areas of a city. Given the strong environmental gradients within short distances of a city, the local monitoring of environmental parameters such as solar radiation and wind speed, which can vary significantly over short distances, becomes critical. Mobile environmental sensing platforms have been used to develop detailed urban environmental monitoring maps for air temperature, solar radiation, relative humidity, wind speed and direction, noise levels, and air contaminant concentrations. Mobile sensing involves the preparation of sensing kits (usually relying on rechargeable batteries) such as MaRTy (Middel and Krayenhoff 2019), Coolbit (Nazarian et al. 2021) that are carried by participants using vests, and wristbands (Croce and Tondini 2022; Wang et al. 2021). While the technical challenges of developing a customary mobile sensing kit and an associated monitoring campaign are non-negligible, the 9% adoption rate in the gathered literature reflects the early development stage in this area of research.

Thermal & sensory surveys and neuropsychological assessments

Subjective thermal comfort has been assessed using thermal surveys in 80% of papers. Sensory surveys have been used to determine subjective comfort due to sensations that include fragrance, sound, or views, and they have been used in only 2% of papers. Acoustic comfort was the most used sensory survey regarding thermal comfort. However, given the small number of papers using sensory surveys, further OTC studies are still needed to evaluate environmental sensorial dimensions.

Limited literature (5% of papers) has used standardized neuropsychological assessments, with subjective neuropsychological assessments used in 4% of papers and objective assessments used in 1% of papers. Subjective neuropsychological assessments were used to gather individuals'self-reported perceptions and experiences in response to OTC. In contrast, objective assessments were used to assess the impact of OTC on cognitive performance, memory capacity, creativity & processing speed. Furthermore, no consensus exists on which neuropsychological assessments or thermal and sensory surveys should be used for OTC observational studies.

No studies have compared subjective and objective assessments in the gathered literature search. Subjective assessments have been mainly used to look into the presence of green infrastructure in the reviewed literature, while little focus has been placed on differences in thermal conditions. POMS has been used to test outdoor thermal comfort in comfortable and uncomfortable urban spaces. On the other hand, the questionnaire STAI has been used in prior literature to look into the role of thermal comfort differences in anxiety levels. However, this research remains limited, and further work is required to understand the assessments that would be most pertinent for the study of thermal comfort and in which cases they should be used.

Physiological sensing for urban OTC assessment

Through the reviewed literature, the importance of cardiovascular (measured by blood pressure, HRV, ECG, PPG, SpO2, RESP), neurological (measured by EEG), and dermatological (measured by ST, EDA, SC, skin humidity) parameters to document psychophysiological comfort can be highlighted (Campbell et al. 2022; Candas and Dufour 2005; Raj et al. 2011).

Physiological sensing focused on cardiovascular functioning was used in 25 papers (11%). This category includes blood pressure, HRV, ECG, PPG, SpO2, and RESP. Due to heat stress, the body's thermoregulatory mechanisms work to dissipate heat, leading to increased blood flow to the skin (Christopoulos et al. 2019). These changes in blood flow were monitored by measuring skin temperature, HRV, and PPG changes (Périard et al. 2021; Zuo et al. 2021).

Physiological sensing focused on neurological functioning was used in 6 papers (3%). This category uses EEG to measure brain activity. EEG instruments were primarily designed for laboratory settings. However, recent advancements have led to the development of mobile EEG devices suitable for outdoor use (Gaoua et al. 2018). Using mobile EEG devices, researchers can gain insights into the brain-cognitive impact of heat stress in urban or natural settings (Tayeb et al. 2022). EEG is highly sensitive and can measure the physiological impact of OTC on cognitive performance. However, interpreting EEG band signals alongside thermal, environmental, and sensory surveys and neuropsychological assessments remains challenging (Cannard et al. 2021; Lang et al. 2022; Mavros et al. 2022). Prior studies agree that more OTC observational studies are required to identify the specific band signals representative of thermal discomfort. And we cannot reach conclusions until more OTC studies are performed using EEG.

Physiological sensing focused on dermatological functioning was used in 38 papers (18%). This category includes ST, EDA, SC, and skin humidity. Skin temperature was reported to be highly reactive to environmental changes (Dzyuban et al. 2022b; Lau and Choi 2021). Prior literature reported that delayed physiological responses have led to observational biases (Havenith 2001) when comparing physiological measures, such as sweat rate, side-by-side with thermal and sensory surveys and neuropsychological assessments (Candas et al. 1979; Sim et al. 2018).

The gathered literature agrees that physiological sensing is important for OTC assessment. However, physiological sensing is still limited to 18% of observational studies. In the reviewed literature, only two studies used physiological sensing on the elderly, and only one used EEG. The reviewed literature also agrees that more OTC observational studies are required to identify the role of gender and age on OTC, and this is yet to be explored using physiological sensing.

Budgetary and technological limitations associated with implementing physiological sensors for an OTC observational study should also be acknowledged. However, physiological sensors are becoming increasingly accessible and cheaper with the growing demand for sensors for monitoring personal health & lifestyle by the general population (Coulby et al. 2020; Henriksen et al. 2018; Liu et al. 2023). For example, including blood pressure, heart rate, and respiratory measurements through smart watches, headbands, and sensors can offer insights into cardiovascular responses to thermal conditions, helping identify potential risks or discomfort related to blood pressure changes (Cannard et al. 2021; Ma et al. 2023; Mansi et al. 2021).

These technological advancements can contribute to bridging the gap in the lack of use of physiological sensing technologies in observational studies focused on urban OTC assessments.

Observational study planning, participants, and demographics

Budgetary constraints must be considered when planning observational studies, especially given the advantages of engaging in bioenvironmental sensing technologies and the observational study logistic preparations, which still require considerable investment. Furthermore, participant recruitment challenges must also be considered. These are also important constraints that will determine the number of participants involved in the observational study and the study duration.

In the literature gathered, most papers (96%) performed cross-sectional studies, and few papers (4%) performed longitudinal studies.

While reaching a large sample is often aimed at cross-sectional studies, longitudinal studies generally rely on small sample sizes to evaluate a specific target group over a longer period. Longitudinal studies allow for more detailed assessments of a specific participant demographic based on factors that include age, gender, and other relevant characteristics specific to the study.

Within the gathered literature, only 3% of the papers focused on the elderly population, and 1% of the studies focused on the younger demographic. Additionally, only 9% of the studies were done in arid climates. As evident in the Sankeymatic diagram shown in Fig. 3, there is an increasing need for more studies that target vulnerable communities, including children and the elderly, across diverse climate conditions.

Proposed framework for OTC observational study planning

Planning a human-centered OTC observational study is a complex, multi-stage process requiring observational study planning and defining environmental, neuropsychological, and physiological data collection practices. These are to be determined and informed by research objectives and strategies. The observational study plan must have considerations for the target population (age, gender, sample size, sampling technique, health & sociocultural background), the chosen site (location, climate), the planned duration of the observational study (time choice, sampling size, study type, i.e., cross-sectional, longitudinal and duration), and potential challenges that might be encountered (budget constraints, lack of equipment, weather). For environmental data collection, it is essential to consider the environmental parameters (air temperature, relative humidity, wind speed and direction, solar radiation, vapor pressure, precipitation, sound level, MRT, globe temperature, luminance, and surface temperature), and geometric parameters (such as SVF). Objective assessments (such as DSB, Stroop test, MMT, TT) and subjective assessments (such as PANAS, POMS, STAI-S, PRS, EV, ROS, and SVS) should be used to evaluate the role of OTC on the mental well-being of people. Thermal surveys (such as TSV, TCV, HSV, TAV, TPV, and others) and sensory surveys (such as AcSV, FSV, VSV, AeSV, and others) should be used to assess participant perception of OTC. Regarding the physiological data, parameters related to cardiovascular (blood pressure, HRV, ECG, PPG, SpO2, RESP), neurological (EEG), and dermatological (ST, EDA, SC, skin humidity) aspects prove useful for OTC assessments (see Fig. 4).

Limitations of this study

This review analyzes the factors/parameters that go into thermal comfort assessments and indices, but it is not an input-data-focused systematic literature review. Another publication focusing on thermal comfort indices will be prepared in future. This literature review does not consider studies written in languages other than English. This review only used PubMed, Scopus, and Web of Science (WoS). Other article search engines could reveal more papers, that have not been explored in this study. Studies that remained unretrievable towards the end of the literature search were also not considered. The literature search is limited to the period from January 1, 2001 to March 21, 2024. Publications after this date were not reviewed.

Conclusions

A systematic review was conducted to summarize the factors and parameters found in the participant-involved OTC observational studies. Using Scopus, Web of Science, and PubMed databases, 8725 papers were retrieved, and following the PRISMA 2021 guidelines, 217 papers were narrowed down. From the observational studies developed in the selected papers, 120 were located in the Global South and 97 in the Global North. Most papers (85) were based on temperate, 80 in tropical, 32 in continental, and 20 in arid climate regions. The population targeted in the observational studies described in the literature ranged from 18 to 60 years (112 papers), with only six papers targeting participants over 60 years and above,

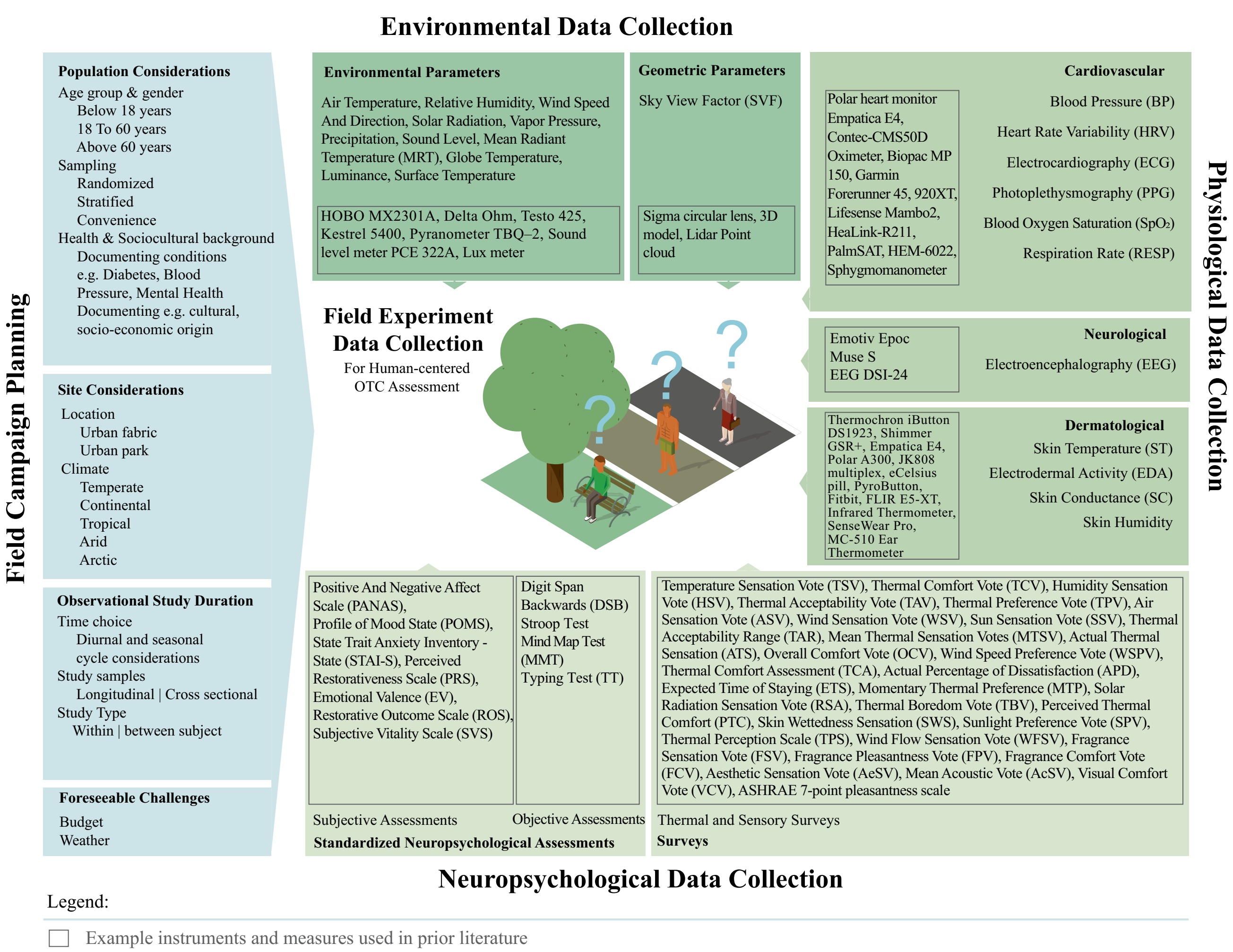

Fig. 4 Framework for OTC observational study planning

three focusing on participants from 0 to 18 years old, and 96 papers did not mention the participant age.

Participant feedback was collected using thermal, environmental, and sensory surveys or standardized neuropsychological assessments. TSV and TCV were the most used thermal surveys and HSV and AcSV were the most used environmental and sensory surveys, respectively. 22 unique thermal surveys and six unique sensory surveys were identified and used in 80% (174 papers) and 2% (five papers), respectively.

Neuropsychological assessments to assess participants' mental state were included in 5% of the selected literature, highlighting the lack of consideration for the role that participants'state plays in understanding OTC. Well-being influences individual experience, with high temperatures worsening mood, increasing depression/anxiety risk, causing irritability, and reducing cognitive performance. This review highlighted that a combination of subjective and objective assessments can be recommended. Objective assessments, such as the DSB task, directly explain how OTC impacts cognition. In contrast, subjective assessments, such as using POMS, allow for assessing the impact of thermal discomfort on mood.

From the selected literature, 18% of papers involved physiological sensing in outdoor environments. The physiological sensing aimed at documenting cardiovascular (measured by blood pressure, HRV, ECG, PPG, SpO2, RESP), neurological (measured by EEG), and dermatological (measured by ST, EDA, SC, skin humidity) functioning.

This literature has highlighted the following research gaps.

i) Previous observational studies centered on psychophysiological thermal comfort assessments have often overlooked the documentation of MRT and SVF despite extensive literature emphasizing the influence of short and long-wave radiation on OTC. Therefore, observational studies incorporating MRT environmental sensing, physiological sensing, and neuropsychological assessments must be developed.
ii) OTC studies conducted in temperate climates, particularly focused in China and Europe, predominate in number. Consequently, there is a pressing need for increased emphasis on observational studies in arid and continental climates.
iii) EEG and HRV biometric sensors are valuable tools for acquiring supportive data in neurological comfort assessments within neuropsychology. However, their potential applicability in psychophysiological OTC assessments remains unexplored. Until recently, physiological sensing technologies used in medical fields, such as electroencephalogram and electrodermal activity, were impractical and off-limits for OTC assessments, given that participants had to be tested in laboratory settings. With novel mobile EEG and multisensory wrist, head, and skin sensors, physiological measures can be more easily captured in complex urban environments.
iv) Objective assessments such as DSB, Stroop Test, MMT, and TT, used to document mood, affect, and emotions, and subjective assessments such as POMS and PANAS used to document cognitive functions and attentional control, are yet to be further studied to assess OTC.
v) Participants involved in psychophysiological OTC observational studies focused on vulnerable communities, particularly children and the elderly, are yet very limited. So are studies focusing on the population suffering from mental health challenges such as anxiety disorder, PTSD, etc., for whom thermal distress can be intensified and require specialized studies.
vi) The investigation of psychophysiological OTC in urban settings has predominantly centered on stationary participants. Yet, in bustling cities, citizens are typically in constant motion. Therefore, delving into mobile sensing technologies, specifically through wearable environmental and psychophysiological sensors, can enhance our comprehension of OTC in connection to urban mobility choices and citizen preferences and behaviors.
vii) Observational studies examining the psychophysiological aspects of OTC during sports activities remain relatively scarce, particularly in light of the growing prevalence of soft mobility modes such as biking, skating, and running in urban areas. Since individuals participating in physical activities through these modes encounter distinct thermal stress, it is necessary to develop focused observational studies to comprehensively evaluate their thermal experiences.
viii) Given the scarcity of observational study endeavors documenting neuropsychological and physiological thermal comfort, the correlation between subjective discomfort reports and physiological responses warrants further investigation.

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MGE supervision, funding acquisition, review & editing manuscript.

EL methodology, review & editing manuscript.

GM review & editing manuscript.

AM methodology, conceptualization, review & editing manuscript.

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Code availability Not applicable.

Declarations

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