# Chapter 11
# Proposed Framework for Establishing a Global Database for Outdoor Thermal Comfort Research

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**Abstract** In the last two decades, studies of subjective thermal comfort have been widely conducted in the urban environment, covering different cultures and climatic regions. However, shortcomings can be observed mainly with respect to protocols used in terms of assessment scales of thermal perception, calculated thermal indices and instrumental setup used for micrometeorological measurements. Such data may vary considerably across studies due to constraints at field sites and the availability of instruments, making it difficult for inter-comparisons between studies and climatic regions, calibrations of thermal indices and a true understanding of people's thermal perception in outdoor settings. There is a need for standardisation of methodology and guidance for conducting field surveys in outdoor spaces with implications on climate-sensitive urban design, public health measures and adaptation of humans to a changing climate. The objective of this proposed framework is to develop a standard methodology for outdoor thermal comfort surveys towards the creation of a worldwide outdoor comfort database.

**Keywords** Data repository · Thermal comfort surveys · Thermal monitoring · Outdoor comfort · UTCI

## 1 Introduction

In the last few decades, climatic effects on the comfort of building occupants have been widely studied in terms of mechanisms and most predominant influencing factors, informing building and urban designers for better design for the comfort and health of building occupants (Olgyay 1963; Givoni 1976; Nicol and Raja 1996).

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E. L. Krüger (ed.), *Applications of the Universal Thermal Climate Index UTCI in Biometeorology*, Biometeorology 4,
https://doi.org/10.1007/978-3-030-76716-7_11

Such advances proved to be important to the health and well-being, as well as productivity and living quality of building occupants (Givoni 1998). The constituents of the physical environment act directly upon human body which tends to achieve biological equilibrium through physical and psychological reactions (Olgyay 1963). As such, the research area dealing with human thermal comfort is focused at the energy exchanges between human body and the climatic environment of the surroundings, and aims to achieve the "comfort" conditions as defined by integrating climatic variables such as temperature, humidity, air movement and radiation.

The shorter time people spent (e.g. in the range of minutes) in the outdoor environment than the indoors also influences the thermal exposure. Höppe (2002) suggested that the steady-state assumption of indoor thermal comfort does not provide realistic assessments for outdoor settings. His previous study based on the Instationary Munich Energy-Balance Model (Höppe 1989) showed that thermo-physiological parameters such as skin and core temperatures take at least one hour in outdoors to achieve the steady-state level. The complex outdoor environment also creates large variations in thermal conditions that the outdoor space users are exposed to. Lau et al. (2019a) showed that subjective thermal sensation changes considerably when pedestrians travel outdoors and suggested that the environmental conditions exposed have a lag effect on thermal perception of pedestrians. Therefore, the assessment of human thermal comfort in outdoor environment requires a different methodological framework and analytical approach in order to address the distinctive relationship between subjective thermal sensation and environmental conditions experienced by outdoor space users. Such short-term acclimatization effects on reported thermal sensation in the context of UTCI applications are discussed in a previous chapter of this book (Chap. 5: Long and short-term acclimatization effects on outdoor thermal perception versus UTCI).

## *1.1 Subjective Assessment of the Thermal Environment*

Conventionally, questionnaire surveys are used to study human thermal comfort to obtain a subjective assessment of the thermal conditions that the respondents are exposed to. There are a wide range of subjective assessment scales for the thermal environment, including perceptual or affective, global or localised, instantaneous or covering certain period of time (ISO 10551 2019). Subjective judgement also varies from the surrounding environment to the person of assessment, from general thermal conditions to specific components such as temperature and air movement, from permanent to temporary situation. The ISO 10,551 provides five subjective judgement scales to describe the thermal state of a person, including thermal perception, thermal comfort, thermal preference, personal acceptability and personal tolerance. The ASHRAE Standard 55 (2017) also provides a scale for thermal perception (commonly known as the ASHRAE 7-point scale) and thermal acceptability (Table 1). However, these standards were not designated for outdoor conditions and their applications in previous studies vary considerably across local contexts.

**Table 1** Protocols for subjective perception of thermal environment (Johansson et al. 2014)

| Parameter | Standard | Interview question and measurement scale |
|---|---|---|
| Thermal sensation or perception | ISO10551<br>ASHRAE | 'How are you feeling now?'<br>7 Point scale: cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (+1), warm (+2) and hot (+3)<br>9-point scale: above plus 'Very cold' (−4) and 'Very hot' (+4) (mainly for use in extreme environments)<br>'What is your general thermal sensation?'<br>7-Point symmetrical thermal perception scale (equal in wording to the ISO 10,551) |
| Thermal comfort (affective evaluation) | ISO10551 | 'Do you find this environment…?'<br>4-Point: comfortable (0) as the point of origin followed by slightly uncomfortable (1), uncomfortable (2), very uncomfortable (3) |
| Thermal preference | ISO10551 | 'Please state how you would prefer it to be now'<br>7-Point: much cooler (−3), cooler (−2), slightly cooler (−1), neither warmer nor cooler (0), a little warmer (+1), warmer (+2) and much warmer (+3) |
| Personal acceptability | ISO10551 | 'On a personal level, this environment is for me…'<br>Two-category statement: acceptable rather than unacceptable (0) and unacceptable rather than acceptable (1)<br>Continuous scale: clearly acceptable, just acceptable, just unacceptable and clearly unacceptable |
| Personal tolerance | ISO10551 | 'Is it…?'<br>5-Point: perfectly tolerable (0), slightly difficult to tolerate (1), fairly difficult to tolerate (2), very difficult to tolerate (3) and intolerable (4) |

There is a lack of standard guidelines or procedures for subjective assessment of the outdoor thermal environment while there are considerable discrepancies in the use of questions and assessment scales. The ASHRAE 7-point scale was commonly used (Krüger and Rossi 2011; Lau et al. 2019b) while 5-point (Nikolopoulou and Lykoudis 2006; Metje et al. 2008) and 9-point scales (Kántor et al. 2012) were also used in some studies for specific purposes. There is usually a middle point in the assessment scale, but the terms used to describe this middle point include "neutral", "comfortable", "neither cool nor warm" and "acceptable". The assessment of other meteorological components, such as solar radiation, air movement and humidity, was also used in some studies (Stathopoulos et al. 2004; Villadiego and Velay-Dabat 2014; Lau et al. 2019b). Moreover, the personal state of thermal comfort (affective evaluation) and thermal preference were sometimes included in the thermal assessment (Oliveira and

Andrade 2007; Ng and Cheng 2012). The inconsistencies in subjective scales and semantics used lead to possible errors in comparisons between results from different studies.

Personal factors such as biological sex, body weight, and skin colour were also found to be associated with the subjective assessment of the thermal environment (Krüger and Drach 2017). It is suggested that variations in thermo-physiological promote changes in adaptation to the thermal environment. Previous studies also suggested that human behaviour is another determinant of thermal perception (Knez and Thorsson 2006), while reasons for visit and cultural background were widely regarded as psychological mechanisms of thermal adaptation in outdoor environments (Nikolopoulou et al. 2001). However, these factors were not addressed by several studies and the methods of assessment need to be standardised to produce more accurate and reliable results.

## *1.2 Thermal Comfort Indices for the Outdoor Environment*

There have been more than 100 different thermal indices developed to describe the heat exchange between the human body and its surrounding environment (Błażejczyk et al. 2012). Energy balance models of human body were developed and widely used in the 1970s–1980s, with a number of biometeorological indices developed for the assessment of thermal stress and strain (Höppe 1997). One of the commonly used indices is the Predicted Mean Vote (PMV) which provides a practical and easily programmable heat balance model of human body (Fanger 1970). It has since been a widely adopted biometeorological index to describe the predicted mean thermal perception under indoor conditions. Pickup and de Dear (2000) developed a physiologically valid outdoor comfort index (OUT_SET*) by adapting the indoor comfort index SET* to outdoor settings. This involves an estimation of the amount of shortwave and longwave radiation absorbed by the human body and hence determines an outdoor mean radiant temperature.

The Munich Energy-balance Model for Individuals (MEMI) was later developed to incorporate individual heat fluxes, body temperatures, sweating rates and skin wettedness into the assessment of the thermal conditions of the human body in a physiologically relevant way (Höppe 1984). It also forms the basis of the Physiological Equivalent Temperature (PET) which is defined as "the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed" (Höppe 1999, p. 71). PET has been used in studies of outdoor thermal comfort in different climates and urban settings (Lin 2009; Ng and Cheng 2012; Krüger 2017).

Another commonly used thermal index which has been widely employed in the last decade is the Universal Thermal Climate Index (UTCI), whose applications are highlighted in this book. The UTCI is defined as "the air temperature which would produce under reference conditions the same thermal strain as in the actual thermal environment" (Błażejczyk et al. 2010). It is therefore a one-dimensional quantity which represents the human physiological reaction to the actual thermal conditions defined by multiple dimensions. It was developed based on the UTCI-Fiala model, which was adapted to predict human responses to outdoor climate conditions. The model also considers behavioural adjustments of the clothing insulation according to outdoor air temperature as well as the effect of air movement, walking speed and clothing's thermal and evaporative resistances (Havenith et al. 2012). The UTCI has been widely used in the assessment of outdoor thermal environments (Bröde et al. 2012; Krüger et al. 2017; Oh et al. 2019—for a more detailed description of such application, refer to Chap. 2 of this book: Literature Review).

## *1.3 Micrometeorological Measurements*

The measurement of micrometeorological conditions is an integral part of outdoor thermal comfort studies since it provides background data for comparisons to subjective thermal perception. Oke (2006) presents a set of guidelines for meteorological observations in urban areas while ISO 7726 (1998) and ASHRAE Handbook of Fundamentals (ASHRAE 2017) also provide a description of instruments that suit thermal comfort measurements for indoors. However, additional considerations are necessary for the adequate exposure of instruments, the measurement of wind speed, and the estimation of the mean radiant temperature $T_{mrt}$ (Johansson et al. 2014).

Temperature and humidity sensors may be affected by radiation sources like solar radiation and heated urban surfaces, leading to overestimation of the air temperature. As such, shielding and ventilation of sensors are required to minimise the radiative exchange between the instrument and its surroundings and avoid the accumulation of warm air around the probe. Cheng et al. (2012) argued that the radiation shield may not be sufficient to prevent overestimation of air temperature so correction to the results may be required. Wind speed is also an important variable in the assessment of thermal comfort and the type of sensors may affect the accuracy of measurements. Two-dimensional anemometers are commonly used but the turbulence outdoors may result in an underestimation of actual wind speed.

$T_{mrt}$ is a critical variable in the assessment of thermal comfort, particularly during warm and sunny weather conditions (Mayer and Höppe 1987) since it represents the aggregated short- and long-wave radiation fluxes in the surroundings that a human body is exposed to (Johansson et al. 2014). It can be determined by two common approaches, namely integral radiation measurements with the inclusion of angular factors and global thermometer combined with measurements of air temperature and wind speed (Thorsson et al. 2007). The large variations in the use of instruments cause inconsistencies and issues in comparisons between studies.

### *1.4 Objectives of the Study*

The present study aims to: (1) prioritise the elements of outdoor thermal comfort studies such as subjective thermal sensation, affective evaluation of thermal comfort, thermal preference for better understanding of human thermal comfort at international level; (2) develop an internationally recognised standard methodology for conducting field studies of outdoor thermal comfort; and (3) establish a database of outdoor thermal comfort surveys by collating existing data from studies conducted in different climates. The methodological framework of the research is described, and the potential applications are discussed. This forms the basis for the broader objectives of the development of the global database of outdoor thermal comfort studies. In connection with the aims of this book, advantages of the proposed repository toward an extensive usage of UTCI are also introduced in this chapter.

## 2 Data Acquisition

### *2.1 Identification and Acquisition of Relevant Data Sources*

Figure 1 shows the methodological framework of the proposed study. At the preliminary stage, a desktop study was conducted to identify relevant data sources for the inclusion in the database. Articles indexed in journal databases such as PubMed, Web of Science, Scopus and SpringerLink were retrieved and shortlisted for relevance, using relevant keywords including (but not limited to) “outdoor thermal comfort”, “human thermal comfort”, “thermal perception”, “thermal assessment”, “outdoor environment” and “questionnaire survey”. The authors of relevant studies were contacted for their interest in contributing to the database. At the same time, a call for contributions to a pilot study was made in the newsletter of the International Association for Urban Climate in mid-2019 (http://www.urban-climate.org/wp-content/uploads/IAUC072.pdf). In the pilot study, there were 20 responses from researchers worldwide covering a range of climatic regions (Fig. 2).

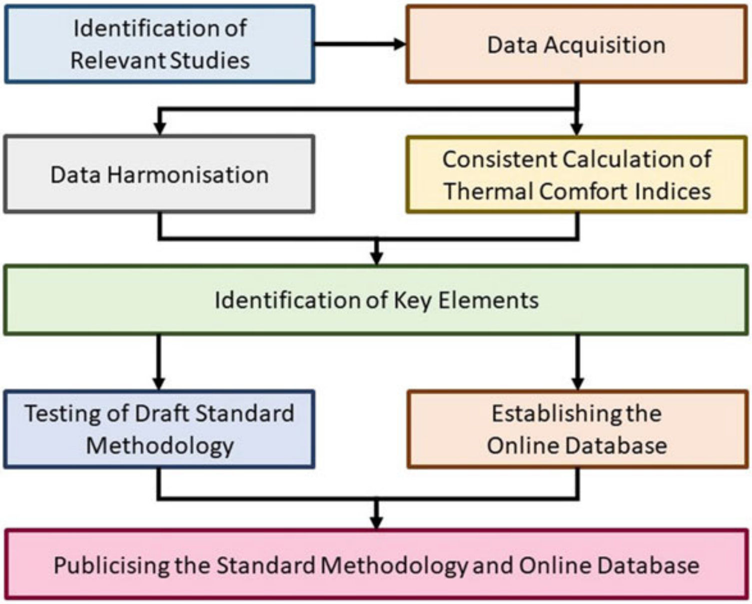


**Fig. 1** Methodological framework of the development of the data repository


**Fig. 2** Locations of the field data from different countries included in the pilot study

Data obtained from shortlisted studies have to fulfil the following criteria in order to be included in the database. A template, consisting of unit of measurements, code names, and coding conventions, was provided for data contributors. Recommendations were as follows:

- Data should be collected from field surveys and experiments conducted in semi-outdoor or outdoor environments;
- Metadata of the study are required, including (but not limited to) dates of questionnaire survey and relevant micrometeorological measurements, number of samples, climate zone and background climatic information, and types of urban settings (with pictures of study site, when available);
- Both subjective (questionnaire survey) and instrumental (micrometeorological measurements) data are required and they should be simultaneously collected to represent the right-here-right-now response from the respondents;
- The questionnaire survey should consist of subjective assessment of the thermal environment, estimated metabolic rate and clothing level of the respondents, immediate thermal history (if any), biometric information, and age and sex of the respondents (when available);
- The micrometeorological measurements should include four fundamental parameters for calculating thermal comfort indices, namely air temperature, humidity, air movement, globe temperature (or three-dimensional measurements of radiation fluxes for calculating mean radiant temperature, $T_{mrt}$). Technical specifications of instruments/sensors and detailed instrumental settings will also be required;
- Raw data are required, i.e. not from processed or published data. However, data must have been published in peer-reviewed journals or conference papers. Therefore, publication metadata should be provided. Coding of the data should also be clearly defined by data contributors.

## 2.2 Data Harmonisation

Subjective thermal perception is often compared to objective micrometeorological measurements in order to understand the subjective–objective relationship of thermal assessment. As different assessment scales (e.g. number of points on the scales) were adopted by previous studies, there is a need to harmonise the datasets obtained from different studies. Table 2 shows the different assessment scales adopted by questionnaire surveys of previous studies. In this study, the ASHRAE 7-point scale will be used as the standard assessment scale for thermal sensation such that studies using 5-point or 9-point scale will be converted to the ASHRAE 7-point scale. The rescaled data were evaluated against the original data based on the mean, variance, kurtosis and skewness values. To further assess whether the rescaled data retain the original structure, data of selected studies were compared to other studies in similar climatic regions.

**Table 2** Different assessment scales adopted by thermal comfort studies

<table>
<tr><td colspan="9">Kántor et al. (2012)—9-point scale</td></tr>
<tr><td>Very cold (−4)</td><td>Cold (−3)</td><td>Cool (−2)</td><td>Slightly cool (−1)</td><td>Neutral (0)</td><td>Slightly warm (+1)</td><td>Warm (+2)</td><td>Hot (+3)</td><td>Very hot (+4)</td></tr>
<tr><td colspan="9">Lau et al. (2019b)—7-point scale</td></tr>
<tr><td>Cold (−3)</td><td colspan="2">Cool (−2)</td><td>Slightly cool (−1)</td><td>Neutral (0)</td><td>Slightly warm (+1)</td><td colspan="2">Warm (+2)</td><td>Hot (+3)</td></tr>
<tr><td colspan="9">Aljawabra and Nikolopoulou (2018)—5-point scale</td></tr>
<tr><td colspan="2">Cold (−2)</td><td colspan="2">Cool (−1)</td><td>Neutral (0)</td><td colspan="2">Warm (+1)</td><td colspan="2">Hot (+2)</td></tr>
</table>

## *2.3 Applicability of UTCI in Regional Comparisons*

Thermal comfort indices are important to provide an objective assessment of the thermal environment. As pointed out by de Dear (1998), there are potential sources of "noise" in the thermal comfort indices since different versions of computer algorithms may have been used to calculate such indices. In order to avoid these inconsistencies, the UTCI is selected and calculated from the raw data of micrometeorological measurements acquired from data contributors. The UTCI has the advantage to represent the assessment of the thermophysiological effects of the atmospheric environment, which is one of the key issues in human biometeorology. The software BioKlima (Błażejczyk 2011) was used to calculate the thermal comfort indices. It provides easy calculations of more than 60 various biometeorological and thermophysiological indices. The mandatory inputs of meteorological variables include air temperature, relative humidity, mean radiant temperature, wind speed, metabolic rate and clothing level (thermal insulation). The resulting UTCI data can then be integrated into the datasets for subsequent data analysis.

As several thermal indices have been used in outdoor studies for quantifying the thermal conditions experienced by individuals, the data repository used the UTCI as the principal thermal index in order to reduce the inconsistencies across different studies. The UTCI was found to be well correlated with other thermal indices, especially those based on human heat balance, e.g. Standard Effective Temperature for outdoor conditions (SET*), Perceived Temperature (PT) and Physiological Equivalent Temperature (PET) (Błażejczyk et al. 2012). This indicates that the UTCI is capable of representing the thermal conditions exposed to human body and the physiological responses to such thermal conditions. The universal assessment scale of the UTCI also allows comparison across different climatic regions and local contexts. This is particularly important for thermal comfort studies as individual adaptations to the thermal conditions vary considerably across local contexts (see Chap. 5: Regional adaptation of the UTCI: comparisons between different datasets in Brazil). By including data acquired from different climatic regions worldwide, the data repository facilitates further studies of how individuals are acclimatised, and their adaptation mechanisms, in terms of physiological, psychological, and cultural perspectives. At a later stage, improvements in UTCI predictions for various climates can be useful for urban designers to provide thermally favourable outdoor spaces in those locations.

One of the potential UTCI applications is in weather forecasting based on synoptic data. Błażejczyk et al. (2012) suggested that the UTCI shows good correlations with synoptic weather variables, by comparing long-term records of air temperature, wind speed, and $T_{mrt}$ acquired from meteorological stations in Freiburg, Germany. It implies the applicability of human-heat-balance-based indices in weather forecasting and provides information of human thermo-physiological conditions for general public and health practitioners to better prepare for extreme weather (hot or cold) conditions. Such application is presented in more detail in Chap. 9: The Universal Thermal Climate Index as an operational forecasting tool of human biometeorological conditions in Europe). As shown in Chap. 2 of this book (Literature review), the applicability of the UTCI was also studied at micro-scale climate by examining field data measured in cold, hot and dry, and hot and humid climates. It was found that the UTCI is generally consistent with most of the thermal indices and it is able to capture the variation of wind speed in cold climate while other thermal indices fail to show such variations (Błażejczyk et al. 2012). Cities and urban built-up areas have specific climatic conditions due to the complex urban geometry (e.g. orientation and disposition of building blocks). Important features of urban climate such as the urban heat island phenomenon, reductions in ventilation, complex spatial variations of exposure to solar radiation at pedestrian level can be well-represented by field measurements and numerical simulation and mapping of the UTCI (cf. Chap. 7: Application of UTCI in high-resolution urban climate modeling techniques). There is thus a great potential of the data repository in terms of facilitating such analyses and feeding them with field measurements carried out in different climatic regions, thereby estimating outdoor thermal conditions based on the UTCI.

## 3 Analytical Procedures

The following subsections outline the necessary steps that shall be taken for establishing the global database for outdoor thermal comfort research.

### *3.1 Identification of Key Elements in Outdoor Thermal Comfort Surveys*

Subjective assessment of the thermal environment includes thermal perception, thermal comfort (affective evaluation), thermal preference, personal acceptability and tolerance (ISO 10551 2019). Data before and after harmonisation must be tested among subjective assessment and objective measurements for the sensitivity in thermal assessment. The non-parametric Spearman's rank correlation coefficient will be used to determine the correlations among subjective assessment and objective measurements, which indicates the significant elements in thermal assessment with respect to micrometeorological conditions that the respondents were exposed to.

Linear regression analysis will be then conducted to investigate the relationship between both original (raw data) and binned values of meteorological variables against diverse thermal comfort indices including the UTCI. At that stage, linear models will be developed to examine how well subjective thermal assessment can be predicted by selected indices from observed meteorological measurements.

The models will be validated using two approaches. Firstly, studies from similar climatic regions or similar urban settings will be divided into training and validation datasets. This ensures the applicability of the models in relatively consistent climatic and environmental conditions. Secondly, the entire datasets will be randomly divided into training (80%) and validation (20%) datasets in order to evaluate the overall predictability of the linear models. The parameters identified will be included in the draft standard methodology which will be further tested by selected research teams in different climatic regions.

## *3.2 Testing of the Draft Standard Methodology*

The key elements identified in data harmonisation will be included in the draft standard methodology which will consist of subjective thermal assessment and micrometeorological measurements. The testing of the draft standard methodology will be conducted in selected countries by corresponding research teams in order to test its feasibility and identify issues or difficulties found by the research teams.

The questionnaire surveys will include the assessment scales and elements determined by the linear models to form the subjective part of data collection. At the same time, the instrumental settings will also be provided for testing the draft standard methodology. The testing will be conducted in different seasons in order to examine the applicability of the draft methodology in both extreme and transitional conditions. The target sample size is 100 responses in each of the four seasons (or relatively different climatic conditions) in order to maintain sufficient samples to compare between different studies and refine the methodology if necessary.

## *3.3 Establishment of the Online Database*

Based on the findings obtained in previous stages, the key elements of human thermal comfort in outdoor environments will be identified and used for establishing the online database. Browser-based applications will be used for readily available and easy-to-use visualisation and user interface. Open-source JavaScript libraries will be used to visualise the data based on the data analysis previously conducted. The primary focus of the database is to provide useful information about the conditions that are perceived as comfortable so that the users such as urban planners and designers can take into account these conditions in their practices.

Four types of information will be included in the database. First, subjective assessment of thermal comfort will be provided to indicate how people perceive their thermal comfort under specific conditions. Second, the corresponding meteorological conditions and derived comfort index results will be provided in order to allow users to understand what conditions are required to achieve thermal comfort. Drawing such relationships will be facilitated not only for a given meteorological variable, which can be analysed individually, but for post-processed comfort indices such as the UTCI, which integrate diverse variables. Third, age and sex of the respondents will be included for any specific use or design of outdoor spaces. Finally, the urban settings where the data were collected will be specified.

During the process of development, a website with online forum will be established to provide an online platform for communication between researchers and contributors. The questions or issues encountered during the process will be shared and data contributors can answer or raise any questions of their own concern. The online platform can also engage potential users during the development process in order to maximise the applicability of the online database. A communication platform will be provided in order to facilitate users' feedback.

## 4 Way Forward

The primary objective of developing this global database for outdoor thermal comfort survey is to provide the empirical basis for establishing outdoor thermal comfort models by understanding the influential elements of human thermal comfort in the outdoor environment. However, the content of the database has a large potential beyond this due to the large amount of high-quality field data that can be used to explore the issues regarding human thermal comfort in the outdoor environment. The followings are some examples of potential applications of this global database.

The database provides numerous possibilities for developing empirical relationships between different assessment scales of subjective thermal perception. Human thermal comfort research has been using a wide range of subjective assessment scales, for example, the seven-point ASHRAE thermal sensation scale, thermal acceptability and preference assessment. The database therefore provides a platform for evaluating the assumptions behind different assessments and their applicability in outdoor settings. By adopting the UTCI as one of the principal thermal indices, regional comparisons may contribute to a better understanding of the contextual effects on subjective thermal perception and the corresponding thermal conditions exposed by individuals in the outdoor environment. It also accommodates the need for understanding the effect of individual characteristics such as biometric parameters and human behaviours on thermal perception.

The contextual effects were studied in some previous work but there have been no comprehensive understandings of how these effects influence subjective thermal perception in different climates. Therefore, there are opportunities for researchers to investigate the characteristics of the outdoor environment and their relationship with human thermal comfort of pedestrians and users of outdoor spaces. Urban planning and design professionals can be informed thereby improving the design of outdoor spaces in order to encourage their usage, which in turn has implications on human health and well-being, as well as energy consumption of buildings.

Since the data provided by researchers have been previously published in peer-reviewed academic journals and undergone the process of quality, they are reliable and ready to use for scientific and design work. The database also allows professional practitioners to extract relevant information for their design. For example, design professionals can acquire the understanding of thermal comfort requirements for specific urban contexts and climatic regions without conducting the field work themselves.

The long-term goal of the database is to establish a standard methodology for conducting outdoor thermal comfort research. The draft version of the standard methodology provided in the later stages of the development of the database allows robust testing of the methodology. It also facilitates comparison of results between different climatic regions and urban settings in order to enhance the understanding of outdoor thermal comfort. This potentially contributes to the discussion of the difference between indoor and outdoor studies, which has been widely discussed in the last two decades.

**Acknowledgements** This work was supported by the Vice-Chancellor's Discretionary Fund of the Chinese University of Hong Kong, Hong Kong.

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