

OPEN

DATA DESCRIPTOR

The Scales Project, a cross-national dataset on the interpretation of thermal perception scales

Marcel Schweiker *et al.*[#]

Thermal discomfort is one of the main triggers for occupants' interactions with components of the built environment such as adjustments of thermostats and/or opening windows and strongly related to the energy use in buildings. Understanding causes for thermal (dis-) comfort is crucial for design and operation of any type of building. The assessment of human thermal perception through rating scales, for example in post-occupancy studies, has been applied for several decades; however, long-existing assumptions related to these rating scales had been questioned by several researchers. The aim of this study was to gain deeper knowledge on contextual influences on the interpretation of thermal perception scales and their verbal anchors by survey participants. A questionnaire was designed and consequently applied in 21 language versions. These surveys were conducted in 57 cities in 30 countries resulting in a dataset containing responses from 8225 participants. The database offers potential for further analysis in the areas of building design and operation, psycho-physical relationships between human perception and the built environment, and linguistic analyses.

Background & Summary

Occupants have a significant influence on their indoor environment and its energy use through their presence and interactions with the building envelope and control system¹⁻⁵. Factors driving occupants-building interactions are linked to either the intention to adjust indoor environmental parameters (e.g. relating to thermal (dis-)comfort), or to non-environmental factors such as leaving the room⁶. The perception of the thermal indoor environment is one important driving factor for actions, including adjustment of heating or cooling set points, or opening windows⁶, which can be described by the adaptive principle: "If a change occurs that produces discomfort, people tend to act to restore their comfort"⁷. Hence, understanding thermal (dis-)comfort is crucial for appropriate design decisions and choosing suitable operation modes in buildings.

According to the widely-used definition by the American Society for Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), "Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation"⁸. Consequently, rating scales are often used for this assessment. Whether a specific set of thermal conditions can be considered comfortable is commonly determined via simple thermal sensation ratings ("cold" to "hot")⁹. In parallel, additional dimensions of thermal perception are known and applied¹⁰; e.g. affective evaluation ("comfortable" to "extremely uncomfortable"), thermal preference ("cooler" to "warmer"), or personal acceptance ("generally acceptable" to "generally unacceptable").

The Scales Project aims at investigating participants' concept relating to verbal anchors of thermal sensation, thermal comfort, and thermal acceptance scales and to review the validity of existing assumptions (see below) regarding the interpretation of responses on these scales. The dataset consists of data from a large-scale international survey applying a newly developed questionnaire, which asks survey participants to state their perceived distance between the verbal anchors. The questionnaire was applied in 21 language versions. Surveys were conducted in 57 cities in 30 countries resulting in a dataset encompassing responses from 8225 participants (Fig. 1). Because individual inputs are available for each dimension of thermal perception, potential analyses and their statistical power benefit from the within-subject nature of this questionnaire.

[#]A full list of authors and their affiliations appears at the end of the paper. *email: marcel.schweiker@kit.edu

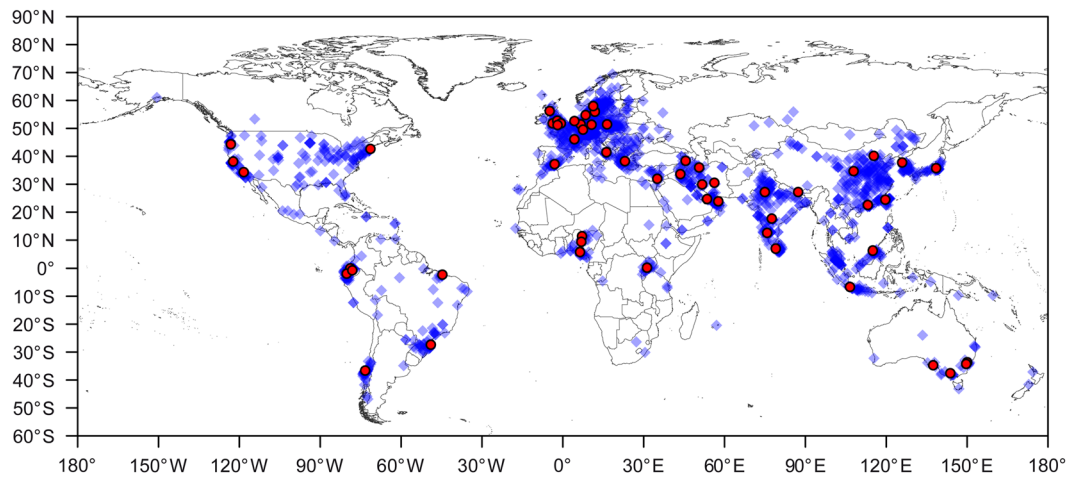


Fig. 1 Applications and participants. Places of application of questionnaires (red dots) and places of origin of the 8225 participants (blue diamonds) in this study.

Following the project's objective, this dataset can be used to analyse the conceptual relationships between verbal anchors of one scale, or between one or more scales. For example, thermal sensation is most frequently assessed using the seven-point ASHRAE thermal sensation scale, with the verbal anchors “cold”, “cool”, “slightly cool”, “neutral”, “slightly warm”, “warm”, and “hot”. A common assumption related to the application of the thermal sensation scale is the assumption of equidistance, meaning the difference between “warm” and “hot” is equal to that between “warm” and “slightly warm”. However, research has questioned this assumption^{9,11–14}. Hence, the applicability of statistical methods relying on them (e.g. linear regression) needs to be questioned. Beyond reviewing the validity of this assumption, the newly developed questionnaire also enables to analyze the influence of different contexts (e.g. language, climate, and season) and characteristics of individuals (e.g. sex). Further assumptions existing for other dimensions of thermal perception, here: thermal comfort and thermal acceptance, can be assessed also.

Another important assumption in the field of thermal comfort to be reviewed through our dataset, postulates that occupants would be satisfied with the indoor thermal conditions, if they chose one of the middle three verbal anchors of the ASHRAE thermal sensation scale (“slightly cool”, “neutral”, or “slightly warm”). In other words, ‘neutrality’ is assumed to be a desired condition. Various studies have shown individual and contextual differences not supporting this assumption^{9,12,13,15–17}. In particular, researchers repeatedly identify a discrepancy in users who declare satisfaction while feeling warm or cool^{18–21}.

In addition, the data can also be used for traditional thermal comfort explorations, with more than 5,031 of the datasets include at least one measurement of indoor temperature. Furthermore, the detailed description and availability of questionnaires, available in multiple languages, can serve as a benchmark for future thermal comfort studies and permit replication to other contexts, for example libraries or offices, or other cohorts such as office workers or older people.

Methods

Questionnaire development and pilot study. Within the framework of IEA EBC Annex 69, an international and interdisciplinary group consisting of 7 independent research groups in 6 countries (Australia, China, Germany, Korea, Sweden, and United Kingdom) – the initial core group – developed the methods applied in the present paper, based on promising results from an experimental study¹⁴. This work included several rounds of face-to-face discussions email conversations as well as an online survey. The details of these discussions together with the description of the methods were submitted and registered to the Open Science Framework (OSF) as a pre-analysis plan (PAP)²². At the time of submission of the PAP, one application of the questionnaire had been conducted, but the corresponding questionnaires were securely stored and untouched until the moment of submission of the PAP.

The initial core group also developed the questionnaire in an English version. Mandarin (with simplified Chinese), German, Korean and Swedish translations were subsequently prepared by native language experts familiar with the concepts used in the questionnaire.

Each group piloted the initial version of the questionnaire according to the following procedure: The questionnaire was applied without further explanation to at least 7 individuals, of which 2 had to be experienced in the field of human thermal comfort. After collecting the questionnaires, researchers discussed with the participants the length of the questionnaire, the clarity of instructions, and issues when filling out the questionnaire. The observations made through these applications were discussed among the core group and reflected in the revised and final versions of the questionnaire.

Expansion of research group. After agreeing on a final version of the questionnaire and submitting the PAP, the initial core group reached out to other researchers in the field through existing networks, such as the

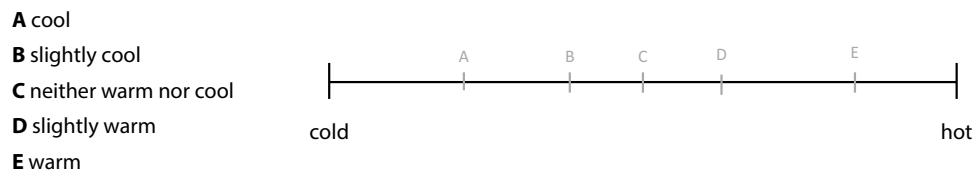


Fig. 2 Exemplary response to one of the free-positioning tasks used in the main part of the questionnaire. Participants were asked to position the verbal anchors shown to the left on the empty line with verbal anchors at extreme positions only. Grey lines and letters present the drawing by one participant. The complete question together with instructions and examples for participants is available online²³.

Network for Comfort and Energy Use in Buildings (NCEUB) (<http://nceub.org.uk/>), and personal contacts. Additional researchers had to sign a co-author agreement and guarantee to follow the procedures prescribed for data collection (see below). In case researchers used other languages than the above mentioned, they had to translate the questionnaire into their language following the same procedure as initially applied – including piloting the new language version with at least 7 individuals beforehand. The number of 7 individuals was based on observations by the initial core group during the first pilot phase revealing that the number of issues raised by test participants concerning the questionnaire do not increase substantially with a higher number of initial respondents. In addition, the project leader checked the questionnaire with respect to the formalities. The final consortium consisted of 56 research groups from 30 countries with a total of 94 individual researchers.

Survey participants. Respondents were university students attending lectures, because they were expected to have only minor variations in age and activity level, supporting the focus on our targeted contextual differences. It was a requirement that the students had not participated in lectures addressing the concept of human thermal comfort. Each respondent could only participate once.

Questionnaire. The questionnaire consists of an introductory page, the two-page main part dealing with the scales and a fourth page addressing the respondents' background and current thermal state (see all language versions in the online repository sites²³). The main part used a newly developed free-positioning task, where participants were asked to position the verbal anchors on a straight line (Fig. 2). In the questionnaire scales relating to thermal sensation, thermal comfort and thermal acceptance were investigated. The first questions prompted participants to process each of these scales individually. Later questions addressed the relationship between (1) thermal sensation and thermal comfort; and (2) thermal sensation and thermal acceptance. Verbal anchors were chosen according to ISO 10551¹⁰. ISO 10551 and many thermal comfort studies also use a preference scale ranging for example from “prefer cooler” to “prefer warmer”. This scale was not used for this study because pilot studies suggested that this scale tends to be misinterpreted by respondents as also pointed out earlier²⁴.

In addition to questions relating to thermal sensation, thermal comfort and thermal acceptance scales (Part 1 of the questionnaire), respondents were asked about their current thermal state and background (Part 2 of the questionnaire). Countries and cities of participants' origin and residence were collated to identify potential adaptations to climatic conditions at the locations where the questionnaires were administered and where participants were living beforehand. See Online-only Table 1 for a full list of variables included in dataset and their source.

Survey procedure. In each country the questionnaire had to be distributed at least twice during two distinct seasons. The requirement for two distinct seasons was lowered for places with only minor variations in outdoor weather conditions throughout the year. Data were collected from a minimum of 100 respondents per country (a minimum of 50 per season).

The following conditions had to be followed for the distribution of the questionnaires:

- Timing: at the end or if necessary during classes, when participants had been seated at least 30 minutes
- Form: paper-pencil
- Language: local language (in case of large groups of foreigners in a country/class (e.g. Chinese in Korea), researchers were free to distribute more than one language version.

On a separate sheet, researchers noted the following additional information:

- City and Country of survey
- Date, start time of distribution and end time of collection
- Number of questionnaires distributed
- Number of questionnaires received back
- Observations made during survey distribution and collection: e.g. “very high noise levels” or “at day of survey it was unnaturally warm for this time of the year”
- Classification of season: This classification was done without any predefined categories and based on individual researchers' decision. The researchers used terms for seasons according to typical terms used at their location. Future users of this dataset, who may plan to include such variable into their analysis, can decide whether they follow the classifications given in the dataset or create their own classifications e.g. based on prevailing outdoor conditions, the date of application, KG class, or other information.

In addition, researchers acquired data of the outdoor conditions (outdoor temperature and humidity) from close-by weather stations (either owned by the researchers, available to researchers, or using public sources) and optionally recorded the indoor conditions during the distribution period. Despite their significant influence on thermal perception, indoor conditions were made optional for the following two reasons.

For the first, the main purpose of the Scales Project was not that of a classic thermal comfort study aiming at the analysis of the relationship between indoor thermal conditions (and other factors) and thermal perception assessed through thermal perception scales. The main objective of this study was to reveal participants' understanding and interpretation of verbal anchors on the scales. The assumption was that they were affected by the prevailing conditions such as seasonal differences or immediate outdoor conditions as well as by an individual's actual thermal state.

For the second, the methodological intention was to maintain a low level of constraints for additional researchers to join this project. Given the aim of a large response rate from a variety of climates and geographical contexts, a decision was made that the availability of measurement equipment should not be a prerequisite for joining. In addition, classical thermal comfort analysis requires the measurement of indoor air temperature, radiant temperature, relative humidity, and air velocity together with the assessment of clothing insulation level. Due to the place of application being university class rooms, temperature distributions in terms of air temperature and also mean radiant temperature could be expected to vary largely among individual positions in a large classroom, e.g. close-by or further away from windows or air outlets. Measuring thermal conditions at each participants' seat would have required substantial amount of equipment significantly limiting the number of participating researchers.

Therefore, a decision was made to have indoor thermal conditions not mandatory and to focus on the assessment of participants' self-reported thermal state. Future users of this data set should be aware of the limitations. Those planning to use recorded indoor air temperatures can still use large parts of the dataset, as 5,031 questionnaires include at least one measurement of indoor air temperature.

Data preparation. Individual research groups prepared the data from their questionnaires and submitted for each application two files: one containing the data transferred from the questionnaire, one containing the additional information for each application. The positions of the labels drawn in the free positioning task were quantified using a ruler and measuring the distance of the positioned label to the left end of each horizontal line.

Upon reception of a dataset, the project leader validated the dataset by means of an automated script (see section Technical validation). In addition, the project leader made the following adjustments to harmonize the data and added further variables by means of an R script available online²³ (see section "Custom code used" below):

Adjustments:

- Researchers participating in this study were advised to print the questionnaire, so that each line representing a linear scale was exactly 100 mm long. This would result in measured distances of verbal anchors between 0 mm and 100 mm. However, there were several cases where the printouts were slightly distorted, i.e. shorter or longer. The real length of the lines in the printouts was reported with the information for each application. Based on this information, the measured values were adjusted for the ratio between the real length of the line in the printed version and the prescribed length of 100 mm.
- Date and time formats were harmonized.
- Season descriptions were harmonized.

Additional variables:

- **KG class:** Koeppen-Geiger (KG) classifications were derived for the place of survey (provided by the researcher), and the places of current residence, previous residence, and origin (as stated by the participants). To obtain the KG class for each combination of city and country, the KG world map (Version March 2017) provided for R (<http://koeppen-geiger.vu-wien.ac.at/present.htm>) was used. This map is based on data from 1986 to 2010 and is the re-analysed KG map with a resolution of 5 arc minutes using the downscaling algorithms²⁵. In order to obtain the KG class automatically, the latitude and longitude were first derived based on Nominatim, the search engine for OpenStreetMap data (<http://nominatim.openstreetmap.org>), then converted to the pixel number of the map.
- **Language type:** The verbal anchors differ in their type between languages (see also¹⁰). In some languages, e.g. English, two adjectives are used on the cool and warm side of the scale, respectively, e.g. "warm" and "hot". Data entries from these languages were assigned the language type "2". Other languages, e.g. Portuguese, use only one adjective on each side, e.g. "frio". These are language type "1". In addition, few languages use either two adjectives on the hot side and one on the cold side ("3h") or vice versa ("3c").
- **Adaptation level:** Depending on the answers to the places of current and previous residence, this variable had the levels: "low", "middle", or "high". The coding was based on the length of residency and the KG classes of current and previous place of living. "Low" denotes that the respondent was living less than a year in the current KG class and that the previous place had a different KG class. "Middle" was assigned to those living 1 to 3 years in the current KG class, but a different one before. All others, i.e. living more than 3 years in the current KG class are "high".
- **Native:** The variable native speaker was a binary variable (yes/no) generated. Responses are marked as "yes", in case the language of the questionnaire is equal to (one of) the language(s) spoken in the country of origin of the respondent. All other responses were marked as "no".

- Country of residence plausible: Participants reported their country of residence. This record was compared to the country of application noted by the researcher. In case these two countries differed (52 responses), the new variable “Country of residence plausible” was set to “no”, otherwise “yes”.

The variables available in the dataset, including their measurement scale, and levels (if applicable) are presented in Online-only Table 1.

Ethics and consent. Ethic approvals were acquired where institutional or national requirements made it necessary, such as the Institutional Review Board’s approval. Informed consent was obtained from all subjects before conducting the survey.

Data Records

All data records listed in this section are available from the project page²³ on OSF and can be downloaded without an OSF account. The information regarding the cities of current residence, previous residence and origin were removed, as they can serve to identify an individual participant. The R script used for pre-processing the semi-raw data is also available. The data were licensed under a CC0 1.0 Universal license.

Data structure. *All Datasets.* File format: comma separated values file (.csv).

These files contain:

- Individual raw datasets without information on cities
 - survData: file containing participants responses
 - survInfo: file containing researcher observations
 - summary reports: Summary report by researcher for each application
- One changelog-File: Record of changes made to raw datasets
- Codebooks for each raw data
- Combined dataset including all information from survData and survInfo file together with additional variables.

Questionnaires. File format: Adobe pdf (.pdf).

These files contain the 21 language versions used.

Data templates. File format: Microsoft Excel (.xlsx).

These files contain the data templates used for data collection.

R Scripts. File format: plain text files (.R)

These files contain the R Scripts used for processing the raw datasets, technical validation, and additional variables.

Technical Validation

Incoming datasets were rigorously checked in several steps:

- (1) Visual inspection of the datasets, whether they comply with the prescribed formats. If not, datasets were send back to researchers.
- (2) Semi-automated R Script to validate
 - a. Spelling of country names, city names, and language codes
 - b. Whether KG class can be derived automatically (otherwise KG class was added manually)
 - c. Whether data points are within the expected range (e.g. relative humidity between 0 and 100%), or one of the available categories (e.g. only one of 7 age groups)
- (3) Additional checks. After combining all datasets, combinations of data points were validated. For example, it can be expected that the verbal anchors of the sensation scale are drawn in the right order, i.e. from cold to hot. Responses, where the verbal anchors for the sensation scale were not in this order were flagged. In addition, outliers were flagged in case a multi-variate regression analysis detected them as outliers. The project leader informed researchers of those data points being flagged and requested an additional check of the original questionnaire. These validations looking for data consistency revealed that the answer patterns in questions 1a, 2a, and 3a, for 266, 307, and 84 questionnaires, respectively, did not meet the researchers’ expectations. The additional checks showed, that one researcher did not understand parts of the instruction of data entry correctly and repeated the data entry again. In the other cases, only 49, 34, 5 values were not correctly transferred, i.e. in 81.6%, 88.9%, 94%, the data was correctly transferred. In case there were more than 10% of data points flagged per one application, the project leader checked the validity of data entries at a random base based on scans of original questionnaires provided by the submitting researchers.

Usage Notes

For further analyses, it is recommended to use the final dataset on OSF and not the individual raw datasets, because revisions by data providers have only been made on the final dataset.

In total, 9111 questionnaires were distributed and 8225 responses collected (90% response rate). Note that the dataset provided consists of all 8225 questionnaires submitted. The authors did not want to exclude any questionnaire from the dataset based on specific exclusion criteria, e.g. outlier definition or completeness of questionnaire. Future users of the dataset can make their own decisions, which questionnaires they consider as valid or not. Any exclusion criteria from the authors' side, would limit the freedom of future users to make such decision.

Code availability

R software²⁶ was used for all steps requiring data manipulation described above in section Data preparation and below in section Technical validation. Custom code was developed for these steps and is made available (see Code availability below). The custom code consists of three main scripts with additional functions loaded when running the scripts.

The first script (`ScalesSurv_00_DataPreparationAndChecks.r`) contains the steps for initial data screening and calculating additional variables for individual datasets.

The second script (`ScalesSurv_01_LoadAllDatasets_compl_final.R`) combines individual datasets and harmonizes some factor levels, e.g. changing all season descriptors "fall" to "autumn" for consistency with other descriptors.

The third script (`ScalesSurv_02_Prepare_Data_final.R`) is used for additional data preparations, such as additional harmonisations and adjustments to individual data points based on the results from technical validation.

All R scripts used for validating incoming data, acquiring climate classifications, and calculating additional variables are available on OSF²³. The R version used for processing the data was 3.5.2 (2019-04-23). The packages used for data preparation and validation were: `knitr`, `gridExtra`, `grid`, `ggplot2`, `pander`, `xtable`, `png`, `kableExtra`, `reshape2`, `SparseM`, `plyr`, `data.table`.

Received: 8 May 2019; Accepted: 16 August 2019;

Published online: 26 November 2019

References

- Andersen, S., Andersen, R. K. & Olesen, B. W. Influence of heat cost allocation on occupants' control of indoor environment in 56 apartments: studied with measurements, interviews and questionnaires. *Build. Environ* **101**, 1–8 (2016).
- Andersen, R. K. The Influence of Occupants' Behaviour on Energy Consumption Investigated in 290 Identical Dwellings and in 35 Apartments. In *Proceedings of Healthy Buildings 2012, Brisbane, Australia* (2012).
- Blight, T. S. & Coley, D. A. Sensitivity analysis of the effect of occupant behaviour on the energy consumption of passive house dwellings. *Energy Build* **66**, 183–192 (2013).
- Guerra Santin, O., Itard, L. & Visscher, H. The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy Build* **41**, 1223–1232 (2009).
- Majcen, D., Itard, L. & Visscher, H. Actual and theoretical gas consumption in Dutch dwellings: What causes the differences? *Energy Policy* **61**, 460–471 (2013).
- Schweiker, M., Carlucci, S., Andersen, R. K., Dong, B. & O'Brien, W. Occupancy and Occupants' Actions. In *Exploring Occupant Behavior in Buildings* (eds Wagner, A., O'Brien, W. & Dong, B.) 7–38 (Springer, 2018).
- Nicol, F. & Humphreys, M. A. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy Build* **34**, 563–572 (2002).
- ASHRAE. Standard 55-2017. Thermal environmental conditions for human occupancy. *Am. Soc. Heating, Refrig. Air-Conditioning Eng. Atlanta, USA* (2017).
- Schweiker, M. *et al.* Challenging the assumptions for thermal sensation scales. *Build. Res. Inf* **45**, 572–589 (2017).
- ISO. ISO 10551. Ergonomics of the thermal environment—Assessment of the influence of the thermal environment using subjective judgment scales (2001).
- Al-Khatiri, H. & Gadi, M. B. Collective understanding of ASHRAE thermal sensation phrases among Arab students. In *10th Windsor Conference - Rethinking Comfort* (eds Brotas, L., Roaf, S., Nicol, F. & Humphreys, M.) 357–370 (NCEUB, 2018).
- Humphreys, M. A., Nicol, F. & Roaf, S. *Adaptive thermal comfort: foundations and analysis*. (Routledge, 2016).
- Pitts, A. The language and semantics of thermal comfort. In *Windsor Conference: Comfort and Energy Use in Buildings 1–7* (NCEUB, 2006).
- Fuchs, X., Becker, S., Schakib-Ekbatan, K. & Schweiker, M. Subgroups holding different conceptions of scales rate room temperatures differently. *Build. Environ* **128**, 236–247 (2018).
- Mayer, E. Ist die bisherige Zuordnung von PMV und PPD noch richtig? *KI Luft-und Kältetechnik* **34**, 575–577 (1998).
- Van Hoof, J. Forty years of Fanger's model of thermal comfort: comfort for all? *Indoor Air* **18**, 182–201 (2008).
- Al-Khatiri, H. & Gadi, M. B. Investigating the behaviour of ASHRAE, Bedford, and Nicol thermal scales when translated into the Arabic language. *Build. Environ*. **151**, 348–355 (2019).
- Humphreys, M. A. & Hancock, M. Do people like to feel 'neutral?': Exploring the variation of the desired thermal sensation on the ASHRAE scale. *Energy Build* **39**, 867–874 (2007).
- Fountain, M., Brager, G. & De Dear, R. Expectations of indoor climate control. *Energy Build* **24**, 179–182 (1996).
- Shahzad, S., Brennan, J., Theodosopoulos, D., Calautit, J. K. & Hughes, B. R. Does a neutral thermal sensation determine thermal comfort? *Build. Serv. Eng. Res. Technol.* **39**, 183–195 (2018).
- Buratti, C. & Ricciardi, P. Adaptive analysis of thermal comfort in university classrooms: Correlation between experimental data and mathematical models. *Build. Environ* **44**, 674–687 (2009).
- Schweiker, M. *et al.* Contextual differences in the interpretation of thermal perception scales – a large-scale international questionnaire study. *Open Science Framework*. <https://doi.org/10.17605/OSF.IO/PS8R7> (2017).
- Schweiker, M. *et al.* Contextual differences in the interpretation of thermal perception scales – the data base from a large-scale international questionnaire study. *Open Science Framework*, <https://doi.org/10.17605/OSF.IO/9P2GQ> (2019).
- Humphreys, M. A., Nicol, F. & Roaf, S. *Adaptive thermal comfort: foundations and analysis*. (Routledge, 2016).
- Rubel, F., Brugger, K., Haslinger, K. & Auer, I. The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800–2100. *Meteorol. Zeitschrift* **26**, 115–125 (2017).
- R Development Core Team. *R: A Language and Environment for Statistical Computing*. (R Foundation for Statistical Computing, Vienna, Austria, 2012).
- Mahdavi, A. & Taheri, M. An ontology for building monitoring. *J. Build. Perform. Simul* **10**, 499–508 (2017).

28. ISO 639-1:2002. Codes for the representation of names of languages—Part 1: Alpha-2 code (2002).
 29. EN 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics; German version EN 15251:2012 (2012).

Acknowledgements

This project was conducted under the framework of IEA EBC Annex 69. M.Sch., S.B., and K.S.-E. acknowledge funding by the Heidelberg Academy of Sciences and Humanities within the project “Thermal comfort and pain”. M.Sch. is thankful to Prof. F. Nicol to share the information on participation via NCEUB, Prof. A. Wagner, Prof. G. Vrachliotis, and Dr. M. Krause from Karlsruhe Institute of Technology for their support in distributing questionnaires. A.A.-Z. would like to thank all the students from University of Technology- Iraq/Mechanical Engineering Department, who participated by providing answers to the questionnaire. F.A.-A. and the research related to Jordan was supported by M.Sch. H.A.-K. is thankful to Dalal Al-Khatiri, Noor Alhuda Al-Saqri, and Maryam Al-Bartamani for their contribution in distributing the questionnaires. E.Am. is thankful to Eleni Alexandrou of the National Technical University of Athens for her contribution in distributing the questionnaires. B.C. is thankful to the National Natural Science Foundation of China (No. 51521005 and No. 51678330). C.C. is thankful to National Research Foundation of Korea (No. NRF-2017R1A2B4012122) J.-H.C. would like to express gratitude to the USC students who volunteered for the data collection, and a special thanks to Ms. Zhihe Wang, who provided a technical assistance to compile the acquired dataset. S.D.-A. is thankful for the funding support of the TEP-130 R&D group from the US. L.P.E. would like to thank IITM, India for the support and DAAD for the scholarship. G.G. is thankful to Andrés Chico, Freddy Ordoñez, Jesús López (Escuela Politécnica Nacional – EPN), Ricardo Narváez (Universidad Central del Ecuador), Guillermo Soriano (Escuela Superior Politécnica del Litoral - ESPOL), Daniel Quiroz (Universidad Regional Amazónica Ikiam) and Stalin Guamán (Universidad Regional Amazónica Ikiam). S.G. would like to thank the Sustainable Energy Research Group (energy.soton.ac.uk) for supporting this work. D.H. is thankful to all the students from Universiti Malaysia Sabah who participated in the present field study. She is also very grateful to all the lecturers who contributed directly and indirectly in the present study. R.T.H. would like to thank Prof Mahena Stief, Dr. Julia Sonnberger, Stefan Keller, Prof Markus Reppich and Prof Michael Krupp and all HSA students involved for their support. G.M.H. was supported by Research Councils UK (RCUK) Centre for Energy Epidemiology (EP/K011839/1) and UK Research and Innovation through the Centre for Research into Energy Demand Solutions, grant reference number EP/R 035288/1. Q.J. acknowledges the funding by Chalmers Energy Area of Advance and is thankful to Jan-Olof Dalenbäck, Holger Wallbaum, Björn Gross, and Ulrike Rahe. B.K. is thankful for Heatshield, under EU Horizon 2020 grant agreement No 668786 and the Ministerie van Defensie (SOLAR V1605). J.Ko. would like to thank Prof. Jörn Toftum for help with translation of the survey questionnaire. A.K. is appreciative of the volunteer work of Yi-Cheng Lei, Eugene Leung, Bentley Rager, Rachel Rimmer, and Kelly Schoenborn. M.C.J.L. would thank for MOST Taiwan and NTCUST to support the funding and measure instruments. I.M.-R. is thankful to Andrés Chico, Freddy Ordoñez, Jesús López (Escuela Politécnica Nacional – EPN), Ricardo Narváez (Universidad Central del Ecuador), Guillermo Soriano (Escuela Superior Politécnica del Litoral – ESPOL), Daniel Quiroz (Universidad Regional Amazónica Ikiam) and Stalin Guamán (Universidad Regional Amazónica Ikiam). I.R. is thankful to first year Architecture students of University of Moratuwa who volunteered for the data collection. M.Ok. would want to thank all the students from Imo State University, Owerri and Federal Polytechnic, Nekede who participated by providing answers to the questionnaire. M.Ol. would like to thank Tadeo Nedala and Menelik Tibikabire who helped administer the questionnaires. W.O. would like to thank Prof Bruce Lonman for his support and all CUHK students involved. The study is supported by General Research Fund, Research Grant Council, Hong Kong (Project code: 14629516) and Vice-Chancellor’s One-off Discretionary Fund of the Chinese University of Hong Kong. A.L.P.A. would like to thank the Civil Engineering students of IFSC who volunteered for the data collection. M.I.R. is appreciative of the volunteer work of Yi-Cheng Lei, Eugene Leung, Bentley Rager, Rachel Rimmer, and Kelly Schoenborn. V.S.’s involvement in the project was partially funded through the Special Study Program provided by The Faculty of Professions, University of Adelaide. D.T. would like to thank Vinnova (Sweden’s Innovation Agency) and her colleagues at the Division of Building Services Engineering for their support.

Author contributions

All authors provided feedback on all steps, especially critical feedback on the paper, and data collection. M.Sch. conceived of the idea (together with S.B. and K.S.), organized the project, wrote the R scripts and the manuscript, contributed to datasets DEKIT, was involved in preparing the English version, translating and piloting the German version and development of methods. A.A.-Z. contributed to datasets IQTUB. M.A.d.A. contributed to datasets BR, was involved in translating and piloting the Portuguese version. F.A.-A. contributed to datasets JOGJU, was involved in translating and piloting the Arabic version. H.A.-K. contributed to datasets OMSQU. R.R.A. contributed to datasets IDITB was involved in translating and piloting the Indonesian version. H.A. contributed to datasets DEBUW. R.A. contributed to datasets GBUOS and GBUCL. E.Am. contributed to datasets GRCUA, was involved in translating and piloting the Greek version. A.Y.A. contributed to datasets USMIT. M.A. contributed to datasets GBCOV. E.Az. contributed to datasets AEKUS. B.B. contributed to datasets IRSHZ, was involved in translating and piloting the Farsi version. A.B. contributed to datasets NGBUA. S.B. contributed to datasets DEKIT, was involved in preparing the English version, translating and piloting the German version and development of methods. C.B. contributed to datasets BR, was involved in translating and piloting the Portuguese version. B.C. contributed to datasets CNTHU, was involved in translating and piloting the simplified Chinese version. J.-H.C. contributed to datasets USUSC. C.C. contributed to datasets KRYON, was involved in translating and piloting the Korean version. H.D. contributed to datasets NLVUA. S.A.D. contributed to datasets IDITB was involved in translating and piloting the Indonesian version. L.D. contributed to datasets AUUOA. R.D.V. contributed to datasets BR, was involved in translating and piloting the Portuguese version. S.D. contributed to datasets INJAI and INHYD. S.D.-A. contributed to datasets ESUSE, was involved in translating and piloting the Spanish (Spain) version. E.D. contributed to datasets PLPWR, was involved in translating and piloting the Polish version. L.P.E. contributed to data preparation and

checks. J.F.-A. contributed to datasets ESUSE. M.F. contributed to datasets NLVUA. A.F. contributed to datasets NLVUA. G.G. contributed to datasets EC. V.G. contributed to datasets INJAI and INHYD. S.G. contributed to datasets GBUOS and GBUCL, was involved in preparing and piloting the English version and developments of methods. S.G.J. contributed to datasets IRTIA. D.H. contributed to datasets MYUMS, was involved in translating and piloting the Malaysian version. R.T.H. contributed to datasets DEHSA, was involved in preparing the English version, translating and piloting the German version and development of methods. G.M.H. contributed to datasets GBUOS and GBUCL, was involved in preparing and piloting the English version and developments of methods. Q.J. contributed to datasets SECTH05 and 06. M.J. contributed to datasets GBCOV. R.K. contributed data preparation and checks. J.Ki. contributed to datasets AUSYD, was involved in preparing and piloting the English version and developments of methods. N.K. contributed to datasets AEKUS. B.K. contributed to datasets NLVUA. M.D.K. contributed to datasets IDITB. J.Ko. contributed to datasets DKDTU, was involved in translating and piloting the Danish version. S.K. contributed to datasets INJAI and INHYD. A.K. contributed to datasets USUOR. R.L. contributed to datasets BR. M.L. contributed to datasets PLPWR, was involved in translating and piloting the Polish version. M.C.J.L. contributed to datasets TWNUT, was involved in preparing the English version, translating and piloting the traditional Chinese version and development of methods. Y.L. contributed to datasets KRYON. V.L. contributed to datasets DEHSA. M.M. contributed to datasets IRKER. U.M.-O. contributed to datasets NGIMS. L.M.-R. contributed to datasets CLUBB, was involved in translating and piloting the Spanish (Chile) version. A.M. contributed to datasets DEUKL. F.M. contributed to datasets ITPBA, was involved in translating and piloting the Italian version. J.M. contributed to datasets INJAI and INHYD. G.M. contributed to datasets UKGSA. I.M.-R. contributed to datasets EC, was involved in translating and piloting the Spanish (Ecuador) version. D.M. contributed to datasets CNTHU, was involved in preparing the English version, translating and piloting the simplified Chinese version and development of methods. B.M. contributed to datasets FRCEP, was involved in translating and piloting the French version. M.N. contributed to datasets USUCB. E.N. contributed to datasets HKCHU. M.Ok. contributed to datasets NGIMS. M.Ol. contributed to datasets UGNKZ. W.O. contributed to datasets HKCHU. A.L.P.A. contributed to datasets BR. A.P.-F. contributed to datasets CLUBB, was involved in translating and piloting the Spanish (Chile) version. I.R. contributed to datasets LKUOM, was involved in translating and piloting the Sinhalese version. G.R. contributed to datasets BR, was involved in translating and piloting the Portuguese version. S.R. contributed to datasets IQUOB, IQTUB and IQNAH, was involved in translating and piloting the Arabic version. C.F.R. contributed to datasets USMIT. M.I.R. contributed to datasets USUOR. M.Sa. contributed to datasets IRKER. K.S.-E. contributed to datasets DEKIT, was involved in preparing the English version, translating and piloting the German version and development of methods. S.Sch. contributed to datasets USUCB. S.Sh contributed to datasets AURMI. M.Shk. contributed to datasets JPTCU, was involved in translating and piloting the Japanese version. V.S. contributed to datasets USUCB. S.Su. contributed to datasets IDITB was involved in translating and piloting the Indonesian version. M.Ta. contributed to datasets IRSBU. F.T. contributed to datasets AUUOW. D.T. contributed to datasets SECTH01 to 04, was involved in preparing the English version, translating and piloting the Swedish version and development of methods. P.T. contributed to datasets INJAI and INHYD. S.T. contributed to datasets INSAL. M.Tr. contributed to datasets CLUBB, was involved in translating and piloting the Spanish (Chile) version. J.T. contributed to datasets DEUKL. R.B.T. contributed to datasets NGABU. C.V. contributed to datasets DEBUW. Y.Y. contributed to datasets HKCHU. L.Y. contributed to datasets CNXIA. G.Z.-L. contributed to datasets GBCAR. Y.Zhai. contributed to datasets CNXIA. Y.Zhu. contributed to datasets CNTHU, was involved in translating and piloting the simplified Chinese version. Z.Z. contributed to datasets IRSBU and IRTIA, was involved in translating and piloting the Farsi version.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to M. Schweiker.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

The Creative Commons Public Domain Dedication waiver <http://creativecommons.org/publicdomain/zero/1.0/> applies to the metadata files associated with this article.

© The Author(s) 2019

Marcel Schweiker^{1,2*}, Amar Abdul-Zahra³, Maíra André⁴, Farah Al-Atrash⁵, Hanan Al-Khatiri⁶, Rea Risky Alprians⁷, Hayder Alsaad⁸, Rucha Amin⁹, Eleni Ampatzi¹⁰, Alpha Jacob Arsano¹¹, Montazami Azadeh¹², Elie Azar¹³, Bannazadeh Bahareh¹⁴, Amina Batagarawa¹⁵, Susanne Becker¹⁶, Carolina Buonocore¹⁷, Bin Cao¹⁸, Joon-Ho Choi¹⁹, Chungyoon Chun²⁰, Hein Daanen²¹, Siti Aisyah Damiaty⁷, Lyrian Daniel²², Renata De Vecchi⁴, Shivraj Dhaka²³, Samuel Domínguez-Amarillo²⁴, Edyta Dudkiewicz²⁵, Lakshmi Prabha Edappilly^{1,26}, Jessica Fernández-Agüera²⁴, Mireille Folkerts²¹, Arjan Frijns²⁷, Gabriel Gaona²⁸, Vishal Garg²⁹, Stephanie Gauthier⁹, Shahla Ghaffari Jabbari³⁰, Djamila Harimi³¹, Runa T. Hellwig^{32,33}, Gesche M. Huebner³⁴, Quan Jin³⁵, Mina Jowkar³⁶, Renate Kania¹, Jungsoo Kim³⁷, Nelson King¹³, Boris Kingma^{38,39}, M. Donny Koerniawan⁷, Jakub Kolarik⁴⁰, Shailendra Kumar⁴¹, Alison Kwok⁴², Roberto Lamberts⁴, Marta Laska²⁵, M. C. Jeffrey Lee⁴³, Yoonhee Lee¹⁹, Vanessa Lindermayr³³, Mohammadbagher Mahaki⁴⁴, Udochukwu Marcel-Okafor⁴⁵, Laura Marín-Restrepo⁴⁶, Anna Marquardsen⁴⁷, Francesco Martellotta⁴⁸, Jyotirmay Mathur⁴¹, Gráinne McGill⁴⁹, Isabel Mino-Rodríguez⁵⁰, Di Mou¹⁸, Bassam Moujalled⁵¹, Mia Nakajima⁵², Edward Ng⁵³, Marcellinus Okafor⁵⁴, Mark Olweny⁵⁵, Wanlu Ouyang⁵⁶, Ana Ligia Papst de Abreu⁵⁷, Alexis Pérez-Fargallo⁵⁸, Indrika Rajapaksha⁵⁹, Greici Ramos⁴, Saif Rashid⁶⁰, Christoph F. Reinhart¹¹, Ma. Isabel Rivera^{42,61}, Mazyar Salmanzadeh⁴⁴, Karin Schakib-Ekbatan², Stefano Schiavon⁵², Salman Shooshtarian⁶², Masanori Shukuya⁶³, Veronica Soebarto^{21,52}, Suhendri⁷, Mohammad Tahsildoost⁶⁴, Federico Tartarini⁶⁵, Despoina Teli^{9,66}, Priyam Tewari⁴¹, Samar Thapa⁶⁷, Maureen Trebilcock⁶⁸, Jörg Trojan⁶⁹, Ruqayyatu B. Tukur¹⁵, Conrad Voelker⁸, Yeung Yam⁷⁰, Liu Yang⁷¹, Gabriela Zapata-Lancaster⁷², Yongchao Zhai⁷¹, Yingxin Zhu¹⁸ & Zahra Sadat Zomorodian⁶⁴

¹Building Science Group, Karlsruhe Institute of Technology, Englerstr. 7, 76131, Karlsruhe, Germany. ²WIN-Kolleg Thermal comfort and pain, Heidelberg Academy of Sciences and Humanities, Karlstr. 4, 69117, Heidelberg, Germany. ³Mechanical Engineering Department, University of Technology, Iraq, Al sinaea, 10066, Baghdad, Iraq. ⁴CTC/Department of Civil Engineering, Federal University of Santa Catarina, Rua João Pio Duarte Silva, s/n. Córrego Grande, 88.040-901, Florianópolis, SC, Brazil. ⁵School of Architecture and Built Environment, German Jordanian University, Darat Othman Bdeir, 11180, Amman, Jordan. ⁶Civil and Architectural Engineering Department, Sultan Qaboos University, Al-Khod, P.O. Box: 33, P.C: 123, Muscat, Oman. ⁷Laboratory of Building Technology, Department of Architecture, Institut Teknologi Bandung, Ganesha 10, 40132, Bandung, Indonesia. ⁸Department of Building Physics, Bauhaus-University Weimar, Coudraystr. 11A, 99423, Weimar, Germany. ⁹Energy & Climate Change Group, Faculty of Engineering & Physical Sciences, University of Southampton, University Road, SO17 1BJ, Southampton, United Kingdom. ¹⁰Welsh School of Architecture, Cardiff University, King Edward VII Avenue, CF10 3NB, Cardiff, United Kingdom. ¹¹Department of Architecture, Massachusetts Institute of Technology, Massachusetts Ave, 02139, Cambridge, United States of America. ¹²Faculty of Engineering, Environment and Computing, BNE Research Centre, Coventry University, Gulson road, CV1 2JH, Coventry, United Kingdom. ¹³Industrial and Systems Engineering, Khalifa University, Masdar Campus, Building 1B, 54224, Abu Dhabi, United Arab Emirates. ¹⁴Architecture, University of Tehran, Kish International Campus, Niyayesh St., Mirmohanna Blvd, 79416-55665, Kish, Iran. ¹⁵Department of Architecture, Ahmadu Bello University, Zaria, Nigeria, Samaru, Zaria, Nigeria. ¹⁶Department of Cognitive and Clinical Neuroscience, Central Institute of Mental Health, Medical Faculty Mannheim, Heidelberg University, J5, 68159, Mannheim, Germany. ¹⁷CTC/Department of Architecture and Urban Planning, Federal University of Santa Catarina, Campus Trindade, 88040-970, Florianópolis, SC, Brazil. ¹⁸Department of Building Science, School of Architecture, Tsinghua University, Shuangqing Road, 100084, Beijing, China. ¹⁹School of Architecture, University of Southern California, 850 Bloom Walk, Watt Hall 204, 90089-0291, Los Angeles, California, United States of America. ²⁰Department of Interior Architecture and Built Environment, Yonsei University, 50Yonsei-ro, 03722, Seoul, Republic of Korea. ²¹Department of Human Movement Sciences, Faculty of Behavioral and Movement Sciences, Amsterdam Movement Sciences, Vrije Universiteit Amsterdam, Van der Boechorststraat 7, 1081 BT, Amsterdam, The Netherlands. ²²School of Architecture and Built Environment, The University of Adelaide, North Terrace, 5005, Adelaide, Australia. ²³Indian Green Building Council (IGBC), Confederation of Indian Industry (CII), Survey#64, 500084, Hyderabad, India. ²⁴Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Avenida de Reina Mercedes, 2, 41012, Sevilla, Spain. ²⁵Faculty of Environmental Engineering, Wrocław University of Science and Technology, Wybrz. Wyspińskiego 27, 50-370, Wrocław, Poland. ²⁶Department of Civil Engineering, Building Technology and Construction Management, Indian Institute of Technology Madras, Building Sciences Block, 600036, Chennai, India. ²⁷Department of Mechanical Engineering, Eindhoven University of Technology, Groene Loper 3, 5612AE, Eindhoven, The Netherlands. ²⁸Departamento de recursos hídricos y ciencias ambientales, Universidad de Cuenca, Av. 12 de Abril, 10203, Cuenca, Ecuador. ²⁹Centre for IT in Building Science, International Institute of Information Technology (IIIT), Gachibowli, 500032, Hyderabad, India. ³⁰Faculty of Architecture and Urbanism, Tabriz Islamic Art University, Azadi, 5164736931, Tabriz, Iran. ³¹Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400, Kota Kinabalu, Malaysia.

³²Architecture, Design and Media Technology, Aalborg University, Rendsburggade 14, 9000, Aalborg, Denmark. ³³Energy Efficiency Design, Augsburg University of Applied Sciences, An der Hochschule 1, 86161, Augsburg, Germany. ³⁴Energy Institute, University College London, 14 Upper Woburn Place, WC1H 0NN, London, United Kingdom. ³⁵Department of Architecture and Civil Engineering, Chalmers University of Technology, Sven Hultins gata 6, SE-412 96, Gothenburg, Sweden. ³⁶Faculty of Engineering, Environment and Computing, Coventry University, Gulson road, CV1 2JH, Coventry, United Kingdom. ³⁷School of Architecture, Design and Planning, The University of Sydney, Wilkinson Bldg G04, 2006, Sydney, Australia. ³⁸Training and Performance Optimization, The Netherlands Organisation for Applied Sciences, Kampweg 55, 3769 DE, Soesterberg, The Netherlands. ³⁹Department of Nutrition, Exercise and Sports, University of Copenhagen, 2100, Copenhagen, Denmark. ⁴⁰Department of Civil Engineering, Technical University of Denmark, Brovej 118, 2800, Kgs, Lyngby, Denmark. ⁴¹Centre for Energy and Environment, Malaviya National Institute of Technology (MNIT), JLN Marg, 302006, Jaipur, India. ⁴²Department of Architecture, College of Design, University of Oregon, 1206 University of Oregon, 97403, Eugene, United States of America. ⁴³Department of Interior Design, National Taichung University of Science and Technology, 129, Sec. 3, Sanmin Road, 40401, Taichung, Taiwan. ⁴⁴Mechanical Engineering, Shahid Bahonar University of Kerman, Jomhouri, 76169133, Kerman, Iran. ⁴⁵Architecture, Federal Polytechnic, Polytechnic Road, 460262, Nekede, Nigeria. ⁴⁶Faculty of Architecture, Construction and Design, University of Bio-Bio, Avda Collao 1202, 4081112, Concepcion, Chile. ⁴⁷Department of Psychology, University of Koblenz-Landau, Fortstraße 7, 76829, Landau, Germany. ⁴⁸Dipartimento di Scienze dell'Ingegneria Civile e dell'Architettura, Politecnico di Bari, Via Orabona, 4, 70125, Bari, Italy. ⁴⁹Mackintosh Environmental Architecture Research Unit, Glasgow School of Art, 167 Renfrew Street, G3 6RQ, Glasgow, United Kingdom. ⁵⁰Institute for Environmental Design and Engineering, University College London, Gower Street, WC1E 6BT, London, United Kingdom. ⁵¹Project-team BPE, Cerema, 46 Rue St Théobald, 38081, L'Isle d'Abeau, France. ⁵²Center for the Built Environment (CBE), University of California, Berkeley, 232 Wurster Hall #1800, 94720, Berkeley, United States of America. ⁵³School of Architecture, Institute of Future Cities, Institute of Environment, Energy and Sustainability, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong SAR, China. ⁵⁴Architecture, Imo State University, Samek Road, 460222, Owerri, Nigeria. ⁵⁵Faculty of the Built Environment, Uganda Martyrs University, Nkozi, Uganda. ⁵⁶School of Architecture, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong SAR, China. ⁵⁷Department of Civil Construction, Federal Institute of Santa Catarina, Av. Mauro Ramos, 950 - Centro, 88.020-300, Florianópolis, SC, Brazil. ⁵⁸Department of Building Science, University of Bio-Bio, Avda Collao 1202, 4081112, Concepcion, Chile. ⁵⁹Department of Architecture, University of Moratuwa, 10400, Moratuwa, Sri Lanka. ⁶⁰Department of Building Physics/Low Energy Buildings, Technical University Kaiserslautern, Paul-Ehrlich-Straße 29, 67663, Kaiserslautern, Germany. ⁶¹Departamento de Arquitectura, Facultad de Arquitectura, Urbanismo y Geografía, Universidad de Concepción, Barrio Universitario, Casilla 160-C, 4089100, Concepción, Chile. ⁶²Property, Construction and Project Management, RMIT University, Swanston, 3000, Melbourne, Australia. ⁶³Department of Restoration Ecology and Built Environment, Tokyo City University, Ushikubo-Nishi 3-3-1, 224-8551, Yokohama, Japan. ⁶⁴Department of construction, Shahid Beheshti University, Evin, 1983969411, Tehran, Iran. ⁶⁵Sustainable Buildings Research Centre, University of Wollongong, Squires Way, 237, 2500, Wollongong, Australia. ⁶⁶Division of Building Services Engineering, Department of Architecture and Civil Engineering, Chalmers University of Technology, Sven Hultins gata 6, SE-412 96, Göteborg, Sweden. ⁶⁷Department of Environmental Studies, Salesian College, 734219, Sonada, Darjeeling, India. ⁶⁸Department of Nutrition, Exercise and Sports, University of Copenhagen, 2100, Copenhagen, Denmark. ⁶⁹Akademie für angewandte Bewegungswissenschaften gGmbH, Walter-Krause-Str. 11, 68163, Mannheim, Germany. ⁷⁰Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong SAR, China. ⁷¹School of Architecture, Xi'an University of Architecture and Technology, Yanta Road, 710055, Xi'an, China. ⁷²Welsh School of Architecture, Cardiff University, King Edward VII Av., CF10 3NB, Cardiff, United Kingdom.