Instruments and methods in outdoor thermal comfort studies – the need for standardization

Johansson, Erik; Thorsson, Sofia; Emmanuel, Rohinton; Krüger, Eduardo

Published in:
Urban Climate

DOI:
10.1016/j.uclim.2013.12.002

Publication date:
2014

Document Version
Peer reviewed version

Citation for published version (Harvard):
Johansson, E, Thorsson, S, Emmanuel, R & Krüger, E 2014, 'Instruments and methods in outdoor thermal comfort studies – the need for standardization', *Urban Climate*, vol. 10, no. 2, pp. 346–366.
https://doi.org/10.1016/j.uclim.2013.12.002

Instruments and methods in outdoor thermal comfort studies – The need for standardization

Erik Johansson[a], Sofia Thorsson[b], Rohinton Emmanuel[c], Eduardo Krüger[d]

[a]Housing Development & Management, Lund University, Lund, Sweden

[b]Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden

[c]Department of Construction & Surveying, Glasgow Caledonian University, Glasgow, United Kingdom

[d]Department of Civil Construction, Technological University of Paraná, Curitiba, Brazil

Abstract

In this paper we review instruments and methods used to assess outdoor thermal comfort and subjective thermal perception in 26 studies reported in the literature during the last decade, covering a wide range of climates and geographical contexts. We found a great variety of instruments and methods used to measure meteorological variables, especially with respect to the mean radiant temperature and wind speed. Moreover, many different subjective judgement scales were used to assess subjective thermal perception, thermal neutrality and thermal preference and a multitude of thermal indices were used to quantify the combined effect of meteorological variables on thermal perception. The use of a variety of methods makes it difficult to compare results of the different studies. There is thus a need for standardization and to give guidance regarding how to conduct field surveys in outdoor environments. Such standards and guidelines should give advice regarding the choice of measurement sites, type and positioning of instruments, appropriate methods to determine the mean radiant temperature, questionnaire design and suitable thermal comfort indices. These guidelines should also include advice on reporting.

Keywords:

outdoor thermal comfort assessment, micrometeorological measurements, questionnaire surveys, thermal indices, thermal perception, thermal comfort standards

Instruments and methods in outdoor thermal comfort studies – The need for standardization

Abstract

In this paper we review instruments and methods used to assess outdoor thermal comfort and subjective thermal perception in 26 studies reported in the literature during the last decade, covering a wide range of climates and geographical contexts. We found a great variety of instruments and methods used to measure meteorological variables, especially with respect to the mean radiant temperature and wind speed. Moreover, many different subjective judgement scales were used to assess subjective thermal perception, thermal neutrality and thermal preference and a multitude of thermal indices were used to quantify the combined effect of meteorological variables on thermal perception. The use of a variety of methods makes it difficult to compare results of the different studies. There is thus a need for standardization and to give guidance regarding how to conduct field surveys in outdoor environments. Such standards and guidelines should give advice regarding the choice of measurement sites, type and positioning of instruments, appropriate methods to determine the mean radiant temperature, questionnaire design and suitable thermal comfort indices. These guidelines should also include advice on reporting.

Keywords: outdoor thermal comfort assessment, micrometeorological measurements, questionnaire surveys, thermal indices, thermal perception, thermal comfort standards

1. Introduction

During the last decade a number of studies on subjective outdoor thermal comfort in urban areas have been conducted and the numbers have increased each year. These studies have been performed worldwide covering many different climates and cultures. Thus, a significant database exists. An interesting question is whether it would be possible to compare results and to calibrate thermal comfort indices in different climates and cultures in order to reveal differences in thermal comfort conditions and thermal perception between them.

Some comparisons between cities in different climates have been made recently. These include the European Union project RUROS [1,2], that studied the variation of thermal comfort and thermal perception in seven European cities during different seasons, and Kántor et al. [3], who made a comparison of the results from six studies reported in the literature. While the former found strong evidence for adaptation to the local climate – both behaviourally and physiologically – the latter found that a comparison between the studies was hampered by the differences in the methodologies used.

Outdoor thermal comfort, as opposed to indoor comfort, is a relatively new field of research. Increased attention on outdoor environments in the early 2000's have led to the expedient use of methods as well as thermal comfort indices developed for the indoors. This seems to have caused some problems since the outdoor environment is so much more complex than the indoor environment. For example, the spatial and temporal microclimatic variations of meteorological variables are often very large. Other reasons for the difficulty include lack of climate control in outdoor spaces, the subject's physical and socio-cultural adaptation and the wide variation in use and users in the outdoor environment. Thus, an indoor approach cannot be directly transferred to outdoor conditions.

Currently there is no international standard which covers outdoor thermal comfort field surveys. There are, however, several standards and guidelines which cover human biometeorological studies in general but they are, with few exceptions, intended for indoor conditions and/or working environments.

The aim of this study is to review instruments and methods used to measure outdoor thermal comfort conditions and to assess thermal perception during the last decade. This study complements the work of Kántor et al. [3] by including more studies and by concentrating entirely on the methodological part, i.e. micrometeorological measurements, questionnaire design and the interpretation of the results in terms of comfort ranges, thermal neutrality and preferred thermal conditions. This review also includes the available standards and guidelines related to thermal comfort studies, both as regards measurement techniques, questionnaire surveys and assessment of thermal comfort. It is hoped that it will be a first step towards standardization of instruments, methods and reporting used for outdoor thermal comfort analyses before inter-comparisons could be made more meaningfully.

2. Micrometeorological measurements and questionnaires

There are a number of international and national standards, guidelines and handbooks related to measurements of meteorological variables, questionnaire design and calculation of thermal comfort indices. Table 1 shows different standards and guidelines and which aspects they cover.

(Table 1 here)

2.1 Experimental design

In the existing standards, guidelines and handbooks (Table 1) there is no advice on how to design the field survey in terms site selection, appropriate number of sites, required number of subjects, accounting for seasonal climate variations, appropriate time(s) of the day, minimum time period for each survey, description and classification of the characteristics of the sites, etc.

As regards classification of the characteristics of the sites, it is necessary to account for the diversity of urban sites, where the variation in microclimates is far greater than indoors. Therefore a different site sampling strategy is needed. The WMO Guide to Meteorological Instruments and Methods of Observation [12] suggests a simplified classification of urban forms with respect to roughness length, aspect (height-to-width) ratio of urban canyons and percentage of built/hard surfaces. However, a more comprehensive approach such as the Local Climate Zone [13] may be preferable in outdoor urban comfort studies.

2.2 Micrometeorological measurements

Meteorological instruments suitable for measurements in urban areas are presented in [12]. Both ISO 7726 [6] and ASHRAE Handbook of Fundamentals [5] describe instruments suitable for thermal comfort measurements indoors. When outdoors extra consideration must be given to exposure of instruments (such as the shielding and ventilation of air temperature and humidity probes), the measurement of wind speed and of the mean radiant temperature. These issues are explored in detail below.

2.2.1 Instrumental setup, measuring range and accuracy

The recommended heights of the sensors according to ISO 7726 [6] are 0.6 and 1.1 m for sitting and standing subjects, respectively, which represents the centre of gravity of the human body.

ISO 7726 [6] specifies requirements on measuring range and accuracy of instruments for both moderate and thermally stressful environments, see Table 2.

(Table 2 here)

2.2.2 Air temperature and humidity

Temperature and humidity sensors may be heated by radiation sources such as the sun and warm urban surfaces. A temperature probe exposed to solar radiation may overestimate the air temperature by several degrees Celsius. According to existing standards the following should be considered when measuring air temperature and humidity:

- Proper shielding of the probes to minimize radiative exchange between the instrument and its surroundings [6,12];
- Proper ventilation of the radiation shield, preferably using an aspirated shield, to maximize convection and to avoid warm air formation around the probe [12];
- Letting a time of 1½ times the response time of the sensor elapse before measurements can take place, to account for instrument thermal inertia [5,6].

2.2.3 Wind speed

Speed and direction of the wind vary considerably outdoors, and especially in urban areas. The following should be considered when measuring wind speed:

- Preferably three dimensional measurements (measuring horizontal as well as vertical wind speeds) should be performed since the wind direction is very irregular;
- The instruments need to have a quick response time and sufficient accuracy [6];
- The measuring interval should be sufficiently large to be able to measure both low and high speeds, at least in places where high wind speeds are common;
- Cup and propeller anemometers may not be appropriate if low wind speeds are expected, since they have a threshold value below which wind speeds cannot be registered;
- Hot-wire and hot-sphere anemometers can measure low wind speeds but instead have an upper wind speed limit. One-directional hot-wire anemometers are sensitive to the wind direction whereas omni-directional hot-wire and hot-sphere anemometers are insensitive of the wind direction [6].

2.2.4 Mean radiant temperature

The mean radiant temperature (T_{mrt}) is one of the most important variables in assessing the thermal comfort, especially during warm weather conditions and in the outdoors [14]. It is defined as the “uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure” [5] and sums the human body exposure to all short- and long-wave radiation fluxes (direct, diffuse, reflected and emitted) in a given environment.

The T_{mrt} can be determined using several methods. The most accurate way to determine the T_{mrt} outdoors is by integral radiation measurements and the calculation of angular factors (i.e. the proportion of radiation received by the human body from different directions) [15]. The method requires simultaneous measurements of short-wave and long-wave radiation from six directions (east, west, north, south, upward and downward) as shown in Fig 1. The short-wave and long-wave radiation are measured by pyranometers and pyrgeometers, respectively. Although being the most accurate method, the orthogonal instrument setup may cause an instrumental error at high angles of incidence [15]. The T_{mrt} (°C) can be calculated from the Stefan-Boltzmann law according to Equation 1:

$$T_{mrt} = \sqrt[4]{\left(S_{str} / \left(\varepsilon_p \sigma\right)\right)} - 273.15 \tag{1}$$

where: S_{str} is the mean radiant flux density, ε_p is the emissivity of the human body and σ is the Stefan-Boltzmann constant ($5.67 \bullet 10^{-8}$ $Wm^{-2}K^{-4}$). According to Kirchhoff's law of thermal radiation, ε_p is equal to the absorption coefficient for long-wave radiation (standard value 0.97). The S_{str} is calculated according to Equation 2:

$$S_{str} = \alpha_k \sum_{i=1}^{6} K_i F_i + \varepsilon_p \sum_{i=1}^{6} L_i F_i \tag{2}$$

where: K_i are the short-wave radiation fluxes (Wm^{-2}) (i=1-6), L_i are the long-wave radiation fluxes (Wm^{-2}) (i=1-6), F_i are the angular factors (i=1-6) and α_k is the absorption coefficient for short-wave radiation (standard value 0.7).

(Fig. 1 here)

The German guideline VDI 3787 [11] suggests a similar but somewhat simpler and cheaper method where one pyranometer and one pyrgeometer are mounted on a moveable axis. During the observation period the instrument is oriented alternatively to six directions (downward, upward, north, east, south and west). A total measurement time of ten minutes is needed to determine the T_{mrt} [11].

Another method to determine the T_{mrt} is by using a globe thermometer (see Fig. 2) combined with measurements of air temperature and wind speed [15]:

$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.335 \times 10^8 V_a^{0.71}}{\varepsilon\, D^{0.4}} (T_g - T_a) \right]^{1/4} - 273.15 \tag{3}$$

where: T_g is the globe temperature (°C), V_a is the wind speed (ms^{-1}), T_a is the air temperature (°C), D is the globe diameter (m) and ε is the globe emissivity.

The standard globe thermometer for indoors is black painted with a diameter of 150 mm, often made of copper [6]. However, such large and heavy globe thermometers may take 20 to 30 min to reach equilibrium [6,16]. Obviously, globe thermometers having a large time constant are not well suited to measure the T_{mrt} outdoors where radiative fluxes and wind speed change rapidly [16].

Both ISO 7726 [6] and ASHRAE Handbook of Fundamentals [5] recommend a medium grey colour, instead of black, when the globe is exposed to solar radiation to better agree with the outer surface of clothed persons. The 40 mm flat grey globe thermometer shown in Fig. 2, made of a grey painted table tennis ball[1], has been used in several outdoor studies (e.g. [17,18]) and has proven to be accurate, mobile and cheap [15]. The tone of grey is however important. Thorsson et al. [15] used RAL 7001 (flat grey) and found that this tone gives accurate results although it slightly overestimates the T_{mrt} during shady conditions and slightly underestimates it during sunny conditions.

To be able to register sudden variations in T_{mrt} with a globe thermometer, the globe needs to have a sufficiently short response time. To achieve this, the globe should be of small size and have a small heat capacity. Thus, if a metal globe is used, the material needs to be thin [19]. To reduce the sensitivity to wind speed variations, the average wind speed over a sufficiently long period – at least 5 minutes – should be used when calculating T_{mrt} [15].

According to ISO 7726 [6] and ASHRAE Handbook of Fundamentals [5] the shape of the globe influences the measurement of T_{mrt}. An ellipsoid-shaped sensor, which gives a closer approximation of the human shape [20], would probably give a more accurate estimation of the T_{mrt} of a standing person. Still, the spherical shape has proven to work rather well, at least in mid- to high-latitude climates [15].

The formula to calculate T_{mrt} (Eq. 3) should ideally be determined through calibration with integral radiation measurements (as described above and shown in Fig. 1) at each geographical location or at least for a similar climate zone and latitude.

(Fig. 2 here)

Yet another way to estimate the T_{mrt} is by using models such as RayMan [21], SOLWEIG [22] and ENVI-met [23]. In this case the solar radiation has to be measured or simulated and the urban morphology – such as buildings, trees etc., surrounding the studied site – has to be modelled.

2.3 Questionnaires

Questionnaires – or structured interviews – are used to gather data from respondents as regards general personal information (age, gender, clothing etc.), thermal perception, preferences, acceptability, etc.

2.3.1 Subjective perception of the thermal environment

ISO 10551 [10], which is primarily aimed at working environments, suggests five subjective judgement scales to describe the thermal state of a person, namely thermal perception, thermal comfort (affective evaluation), thermal preference, personal acceptability and personal tolerance. ASHRAE 55 [4], which is aimed at indoor applications, includes scales for thermal perception and thermal acceptability. Table 3 shows the judgement scales used in ISO 10551 [10] and ASHRAE 55 [4].

(Table 3 here)

---

[1] The size of a standard table tennis ball was changed from 38 to 40 mm in the year 2000.

2.3.2 Physical activity and clothing insulation

Both the physical activity and clothing of the body strongly affect the thermal perception. Several standards, guidelines and handbooks include information about metabolic rates for typical tasks and the thermal resistance of individual garment and clothing ensembles, see Table 1. The standard ISO 8996 [8] specifies methods to determine metabolic rates for working environments and includes metabolic rates for a number of different tasks. The standard ISO 9920 [9] specifies methods for estimating the thermal characteristics for clothing ensembles based on values for known garments and includes the influence of body movement, air penetration and water vapour resistance.

2.3.3 Psychological mechanisms involved in thermal comfort assessment

A number of studies have illuminated psychological mechanisms involved in outdoor place and thermal comfort assessment (e.g. [2,24,25], including knowledge/experience, attitude/expectations, belief/preferences, perceived control and thermal history. Furthermore it has been shown that culture (rules, norms and values) also influence thermal perception outdoors [26,27]. In the outdoor environment psychological mechanisms may contribute to as much as 50 % of the variance between objective and subjective evaluation of thermal comfort [24]. There is however no standard or handbook giving advice on how to ask questions regarding these aspects.

2.4 Thermal indices

Over the years more than 100 different thermal indices have been developed describing the heat exchange between a human body and its surrounding environment [28]. The great majority of these indices were developed for indoor conditions. Thermal comfort indices can be divided into rational and empirical indices [29]. The former are based on an analysis of the physics of heat transfer, i.e. based on the heat balance equation of the human body. Table 4 shows details on some of these indices. Although many of the indices described in Table 4 were developed for indoor conditions – such as PMV, SET* and ET* – they have also been applied outdoors.

(Table 4 here)

Empirical indices are derived from subjective estimates [29]. One example is the correlation between subjective thermal perception and measured meteorological variables determined through multiple regression analysis, see e.g. [32,33,34]. Such thermal perception predictions may however be restricted to the geographical area, or climate type, where the field survey was conducted.

Both ISO 7730 [7] and ASHRAE 55 [4], which were designed for indoor environments, suggest the use of the Predicted Mean Vote (PMV), whereas the German engineering guidelines VDI 3787 [11], which were developed for use in outdoor environments, suggests the use of PMV, PT and PET. However, existing standards and guidelines have no recommendations on how to calculate the neutral and preferred index temperatures.

3. Methodology

3.1 Choice of studies

This paper is based on a literature review of 26 studies published between 2001 and 2012[2]. The studies were carried out in 28 cities in 19 countries in a great variety of climates covering zones A to D according to Köppen's climate classification, see Table 5. The choice of studies was limited to those containing both micrometeorological measurements and questionnaire surveys with the aim of linking measured thermal conditions with people's subjective thermal perception. Only peer-reviewed journal articles in English were considered, which excludes studies published in other languages and a large number of conference papers, see e.g. [35], so the real amount of studies is likely to be far larger than what is presented here. It should also be noted that some field survey data have been included – fully or partially – in more than one article; for example, [34] and [36] are based on the same field survey but the data have been evaluated in different ways. Although the selection has been limited, the comparison covers a great range of different climates and cultures and gives a good picture of the instruments and methods that have been used. Fig. 3 shows that there has been a sharp increase in the number of studies the latest years (2011 and 2012-13[2]).

(Table 5 here)

(Fig. 3 here)

3.2 Comparison of studies

The comparison looked at the following methodological aspects of the selected studies. Table 6 details the components of each aspect studied:

- Experimental design
- Meteorological measurements
- Questionnaire design
- Thermal indices

(Table 6 here)

4. Results and discussion

4.1 Experimental design

4.1.1 Type of field surveys

Most field surveys used a quasi-experimental design, i.e. subjects were not completely randomly chosen and independent variables may be mixed with uncontrolled variables. This means that the conclusions drawn about the relationships between the independent and dependent variables may be weaker than for "true" experiments [25,55].

Twenty-one (84 %) of the studies, consisted of transversal studies, i.e. surveys in which each person participated only once, whereas 4 (16 %) of the studies were longitudinal, i.e. a limited number of subjects were exposed to different microclimates at different moments of the survey.

---

[2] Some of these studies, which were published on-line during the review in 2012, later appeared in print in 2013.

The number of subjects in the field surveys varied greatly. In general the longitudinal studies comprised of only a few subjects, between 8 and 36, whereas the transversal studies had between 91 and 2700 subjects.

Both transversal and longitudinal methods have their advantages and disadvantages. An advantage with the latter type is a better control that the subjects have the same thermal history. On the other hand a disadvantage may be that the number of subjects is too small to be representative for a larger population. Another aspect not to be disregarded in longitudinal studies is that the subjects could eventually develop a bias towards expected research outcomes.

4.1.2 Type of sites and their description

Most surveys took place in the city centre, but a few studies also included non-central locations and suburbs. Five of the studies were conducted within a university campus. The most common sites were open public spaces such as parks and squares, but pedestrian streets and waterfronts were also common, see Fig. 4. The fact that most studies were conducted in typical public places is relevant since these are places of social interaction and it is therefore important that they are thermally comfortable.

(Fig. 4 here)

The number of sites included in the surveys varied between one and 13; in general, large studies which included many interviews also included more sites. In most studies people who were sitting/standing, or passing by, in the vicinity of the measuring equipment were asked at random to participate in the survey. Many studies using the “random” technique asked the subjects about the reason for being in the place; in this way those that were there on their own free will could be distinguished from those who were just passing by on their way to another place. The reason for being in a place obviously has an impact on the subjective thermal perception. In places where people pass by on their way to a destination (a transition space) the microclimate may not be as important as in a resting place where poor comfort conditions may lead to avoidance of use [2,17].

The chosen sites were normally well described and often illustrated by photographs. However, in a few cases, typically in studies involving a large number of sites, neither descriptions nor illustrations were available. In general, the type of urban environment (whether it was high-rise, low-rise, suburban, etc) was seldom defined. Only six (23 %) of the studies showed the field survey sites on a city map, and only ten (38 %) of the studies had plans or aerial views of the measurement sites and their immediate surroundings. Five (19 %) of studies, however, showed sky view images of the sites and reported the calculated sky view factor.

4.1.3 Time periods of the field surveys

The length of the field surveys varied considerably from study to study, from one single day to a whole year. In most cases (21 studies) more than one season were studied, typically summer and winter. In some cases longer periods such as half a year or a whole year was covered, see Table 7. The time of the day varied a great deal as well. Most studies covered the afternoon, whereas others also included the morning and evening, see Table 7.

(Table 7 here)

A seasonal difference in thermal comfort ranges and/or neutral temperatures was found in almost half (42 %) of the reviewed studies indicating that season influences the thermal perception or how subjects respond to the questionnaires. Thus in climates with distinct seasons the comfort range of indices and neutral temperatures should not be expected to be the same all year round.

It is also important to know whether the studied period was normal for the season. If it was considerably warmer or cooler this may have an impact on the subjective responses Moreover, it is important to know the climate of the period preceding the field survey (at least the nearest days). An unusually warm day during a cold season might lead to an overestimation of the warmth [17]. This could be detected if the climate normals for the measurement period were reported. Less than half of the studies related the measurements to the climate normals. The reporting should preferably include the climate normals as measured at the nearest meteorological station immediately before and during the field survey.

Another important aspect is the time of exposure to the outdoor environment, as it takes time for the human body to adapt. The human body adapts much faster to a warmer environment than to a colder environment. Since outdoor thermal indices, such as PMV and PET are based on steady-state energy-balance models of the human body they may not be appropriate for assessing short-term exposure, especially to cold conditions [56].

4.2 Micrometeorological measurements

4.2.1 Instrumentation

In 16 (62 %) of the studies, the types of instrument used were stated. However, in only half of these studies the accuracy of the instruments was specified. A couple of studies simply stated that the measurement equipment fulfilled the requirements of ISO 7726 [6] without specifying the brand. Nine of the studies (35 %) did not give any specifications of the instruments whatsoever. Moreover, the instrumental setup varied a great deal between the studies, especially with respect to wind and T_{mrt}, two variables that show the largest intra-urban variation. The measurement probes were normally placed at a standard 1.1 m height, except for wind (see below).

It is remarkable that in more than one-third of the studies no information about instrumentation was given. This is a major concern and a sign of low scientific quality of the peer review process. The accuracy of the instruments, as well as the measuring range and response time should also be stated.

With one exception [41] measurements took place in the vicinity of the subjects interviewed. Since large intra-urban variations exist, especially in terms of wind and radiation (T_{mrt}) and thus affect local thermal perception, it is crucial that measurements are conducted near the subjects interviewed, if the aim is to analyse how people perceive the thermal conditions.

4.2.2 Air temperature and humidity

The air temperature and humidity were measured in all the reviewed studies. The measurement probes (mostly a combined probe measuring both variables) were reported to be shielded in some way in twelve (46 %) of the studies. In three of these studies the shield was described whereas the remaining nine studies stated that the measurement setup was in accordance with ISO 7726 [6] or ASHRAE Handbook of Fundamentals [5]. Only one study [2] reported the use of forced ventilation of the temperature probe; in all other studies there was no information whether the ventilation of the radiation shield was natural or forced. Moreover, as many as 54 % of the studies did not state whether the probes were shielded or not. In fact, in one of the reviewed studies [40], it was discovered that the radiation shield used was not sufficient, which led to overestimated air temperatures, and some results had to be corrected.

4.2.3 Wind speed

The wind speed was measured in all studies. Wind measurements were performed using a large variety of anemometers (see Fig. 5), the commonest being the two-dimensional cup anemometer followed by the heated-sphere. It is noteworthy that three-dimensional measurements of the wind speed only took place in two studies (using three-dimensional ultrasonic anemometers). In eleven (42 %) of the studies there was no information whatsoever about which type of anemometer had been used. Since wind speed is a critical variable in assessing the thermal comfort, accurate measurements are required. As mentioned in Section 2.2.4 cup anemometers have a lower threshold value making them inappropriate at low wind speeds, whereas heated-spheres have an upper maximum limit for wind speeds. In one study [16], a combination of both these two type of probes were used to overcome this problem.

(Fig. 5 here)

As shown in Section 2.2.3, anemometers that only measure horizontal wind speeds – such as two-dimensional cup, propeller and ultrasonic anemometers – may underestimate the actual wind speed since urban winds often vary greatly in direction including vertical movements. One-directional hot-wire anemometers, that were used in one study, only measure correctly for wind directions perpendicular to the hot-wire [5,6]. They are therefore not suitable for outdoor use where wind directions vary frequently; instead an omni-directional instrument should be used, see Section 2.2.3.

The measurement height for the wind speed measurements was either the same as for the other probes (in general 1.1 m) or measured at a slightly higher level, typically between 1.5 and 2 m. In these cases the wind speed at 1.1 m was normally estimated using the wind profile power law. This may, however, not be correct if the stability of the atmosphere is not neutral or if the air is very turbulent. In seven studies the measurement height was not specified.

4.2.4 Short- and long-wave radiation

In 19 of the studies (76 %) the global solar radiation was measured. In six of these studies the long-wave radiation was also measured. The instruments used to measure short- and long-wave radiation were specified in 14 (54 %) and five (19 %) of the studies, respectively. In many of these studies, the short-wave (and in some cases also long-wave) radiation was used to calculate T_{mrt}, see below.

4.2.5 Mean radiant temperature

The great majority of the studies (77 %) measured or modelled the T_{mrt}. As shown in Table 8, instruments and methods used to determine the T_{mrt} varied greatly between the studies.

(Table 8 here)

The most common method to determine the T_{mrt}, used in 12 (46 %) of the studies (Table 8) was by using a globe thermometer combined with measurements of air temperature and wind speed. As can be seen in Table 9, the types of globe thermometer varied greatly as regards material, size and colour of the globe. The temperature sensors inside the globe also varied considerably. In general, the characteristics of the globe thermometers were not well described and in three (12 %) of the studies no description at all existed. All of the studies that used the globe thermometer to determine T_{mrt} used formulas from the literature. None of the studies used three-dimensional measurements of the short- and long-wave radiation fluxes (Fig. 1) to obtain T_{mrt} using Eq. 3.

(Table 9 here)

As mentioned in Section 2.2, the shape of the globe thermometer may influence the measured T_{mrt}, especially in outdoor environments where people are more often standing or walking. Thorsson et al. [15] found good correlation between a spherical globe and standing persons in Göteborg, Sweden (latitude 57°), but at lower latitudes, where solar elevations are higher, the T_{mrt} might be overestimated by a round instead of ellipsoid globe.

The fact that the globe thermometer method is rather simple and the instruments are easily accessible at a low cost might explain why this method is frequently used compared to the other methods. However, it is evident from this review that globes designed for indoor, rather than outdoor, use have been used in several cases, e.g. globes with large diameter (above 50 mm), of heavy material (copper) and black-coloured.

The second most common way to determine the T_{mrt} was by modelling, mainly using the model RayMan [21].

The VDI method described in Section 2.2.5 [11] was used in three studies. In one of the studies [16] a similar method was used where incoming (downward) and outgoing (upward) short-wave (direct and diffuse) and long-wave radiation was measured. See Table 8. The disadvantage with the VDI method is that it takes at least 10 minutes to get one value of T_{mrt}. This is longer than the normal time to answer a questionnaire and may be a problem if weather conditions are unstable.

Although the integral measurement method by Thorsson et al. [15] described in Section 2.2.4 (Fig. 1) is accurate and fast, it is costly and complex which might explain the fact that none of the reviewed studies made use of this method.

4.3 Questionnaires

The results presented here refer to what has been reported in each article. In many cases the actual article only presents results from a small proportion of a larger study.

4.3.1 Number of subjects interviewed

As mentioned above the number of subjects in the studies varied greatly, between 8 and 36 for longitudinal studies and between 91 and 2700 subjects for transversal studies. To achieve a desired accuracy and degree of confidence it is important that the sample size is large enough. Furthermore, the sample must represent the general population. The sample size can be estimated from population size, margin of error, confidence level and response distribution. For large populations, acceptable sample sizes range between 400 and 500 individuals; however other aspects such as a good balance of age and gender and the distribution of the interviewees over time (seasonal changes) seem to be more relevant here.

4.3.2 Questionnaire design

Similar to the measurements, there was great variation in the design of the questionnaire. Whereas all studies collected personal information such as age, gender, clothing and activity, only the studies from Curitiba [34,36] and Glasgow [54] collected data about the body mass (height and weight), information needed to calculate the UTCI thermal index, see Section 4.4.1.

All studies except two included a question on thermal perception of the type “How do you feel right now?” followed by a subjective judgement scale (see Table 3). However, different thermal perception scales were used. The most commonly used scale was the so-called ASHRAE 7-point scale which was used in 13 (52 %) of the studies, see Table 3. Four studies used a 9-point and four studies a 5-point scale. In the latter case, the answering alternatives were normally Very cold, Cool, Neutral, Warm and Very warm. However, the middle point was not Neutral in all studies; other middle points used were Comfortable, Neither cool nor warm and Acceptable. In two studies the middle point was not specified.

Stathopoulos et al. [37] used a different type of scale for thermal perception where a number of statements – “the wind force is strong”, “the air temperature is high”, “the air is humid”, “the solar radiation is warm” – were rated on a 5-point scale from Disagree (-2) to Agree (+2) with Uncertain (0) in the middle. Two studies [38,43] used differential (continuous) scales for thermal perception, i.e. values between the fixed values, e.g. +1.2 (between slightly warm and warm), could be chosen. Several studies included perception of other weather variables than temperature, namely wind (14 studies), humidity (12 studies) and solar radiation (11 studies).

Some studies incorrectly used thermal sensation when they referred to people’s perception of the thermal environment. Thermal sensation refers to sensory unconscious detection of environmental stimulation/information by thermal receptors in the skin. Thermal perception on the other hand refers to conscious interpretation and elaboration of sensory data [25].

More than half of the studies (52 %) included some question on preference of the type: “How would you prefer to be now?” The variable most commonly requested was temperature (thermal preference, 13 studies), but preference to other variables such as wind (11 studies), solar radiation (ten studies) and humidity (nine studies) were also frequently asked. Again, different scales were used. Most commonly a 3-point scale, the so-called McIntyre scale (see Table 3), was used (six studies) but 5-point (five studies) and 7-point (2 studies) scales were used as well. In the study by Andrade et al. [47], their 5-point scale was reduced to a 3-point scale during the analysis, since very few interviewees selected the extremes.

About one-third (36 %) of the studies had a question related to the personal state of thermal comfort of the type “Do you find this environment…?” as described in Table 3. However the scales differed somewhat between the studies both as regards the number of points of the scales – which varied between two and seven – and the wording. All scales were different from the 4- or 5-point one-pole scale suggested by ISO 10551 [10], see Table 3. All scales used in the reviewed studies were symmetrical and bi-polar and the most commonly used (3 studies) was a 4-point scale with the answering alternatives Very uncomfortable, Uncomfortable, Comfortable, Very comfortable [39,40,46].

Only four studies explored acceptability. Of these, three used the 2-point scale Acceptable/Unacceptable suggested by ISO 10551 [10], whereas one study used a 5-point scale.

No study recorded responses on tolerance. The reason for this may be because none of the studied environments were extreme.

As demonstrated above, both the number of answering alternatives of the different subjective scales and the wording of these alternatives varied considerably. This constitutes a source of error when comparing the results from different studies.

4.3.3 Physiological and psychological adaptation

Several studies included questions to reveal psychological mechanisms involved in thermal comfort assessment as well as physiological adaptation. The majority (67 %) of the transversal studies had a question regarding the thermal history of the subject, typically where the subject had been the last half hour before the interview to reveal physiological adaptation. Three studies (14 %) asked whether the subject had been indoors or outdoors before the interview. Several studies (43 %) asked a question about the time of residency in order to identify those who were not physically and culturally adapted to the actual climate. More than half (52 %) of the studies asked about the reason for visit to the site in order to distinguish those who were there to enjoy the place from those who were merely passing by. Almost half of the studies (46 %) found evidence for psychological or physiological adaptation.

4.4 Assessment of thermal comfort, neutrality and preference

4.4.1 Calculation and calibration of thermal comfort indices

All studies except four (85 %) determined some kind of thermal index. The type of index varied greatly between the studies, see Fig. 6, and several studies used more than one index. A large majority of the studies (69 %) used one or more rational indices. The most commonly used index was the Physiologically Equivalent Temperature (PET) followed by the Standard Effective Temperature (SET*) and the Predicted Mean Vote (PMV). PMV was mainly used in the early part of the 2000’s whereas the use of PET and SET* has increased in recent years. The reason for this may be that several studies have reported poor correlation between PMV and subjective thermal perception, see e.g. [35,40,49,53,56]. Only one study [36] calculated the newly developed Universal Thermal Climate Index (UTCI).

(Fig. 6 here)

Twelve (46 %) of the studies calibrated the calculated thermal comfort indices against the subjective responses (votes) of thermal perception. Thus, there seems to be a wish to calibrate thermal indices – or adjust the standard comfort zones of the indices – to use them on a national or regional level. However, it will be difficult to compare or analyse differences between different climate zones and cultures if the methods or instrumentations are not standardized.

Most studies that explored the relationship between thermal perception and a calculated thermal index used average values of the subjective thermal perception in temperature bins, typically of 1°C. This improves the correlation.

In three (12 %) of the studies [32,33,34], the relationship between objective measurements and subjective thermal perception – expressed on a scale from –3 to +3 – was determined through multiple regression between subjective thermal perception votes and the measured meteorological variables (typically air temperature, humidity, solar radiation and wind speed) as described in Section 2.4. Predicting thermal perception using empirical methods did not include the variables activity and clothing.

4.4.2 Determination of neutral and preferred temperatures

In more than half of the studies (58 %) the neutral air or index temperatures were determined. However, in only five (19 %) of the studies the preferred air or index temperatures were determined.

5. Conclusions and future work

This study consisted of a review of instruments and methods used in outdoor thermal comfort studies since 2001. A sharp increase in the number of studies has occurred in recent years. This is evidence for an increased attention to outdoor public spaces. However, our ability to define outdoor thermal comfort limits or to compare thermal comfort limits between different environments is predicated on the standardization of measurement methods and reporting.

This review concluded that there is a great variety of instruments and methods used in outdoor thermal comfort surveys, both as regards micrometeorological instruments, questionnaire design and thermal indices. The instruments and methods used to obtain T_{mrt} and wind speed, two of the most important meteorological variables that influence the human energy balance and assessment of thermal comfort, varied greatly in the selected studies. It was also noted that measurement equipment, accuracy and response time were not stated in the majority of the studies. Furthermore, the subjective judgement scales to determine thermal perception, thermal preference etc. were different from study to study both as regards number of answering alternatives and wording. Moreover, a wide range of thermal indices (nine), most of them rational, were used to quantify the combined effect of meteorological variables on thermal perception. The descriptions of the urban sites were often poor.

There exist a number of standards, guidelines and handbooks and they are useful in many ways. Still, most of them are designed for indoor conditions or working environments. Moreover, some of the standards are out-of-date, e.g. the ISO standards which concern measurements, ISO 7726 [6], and subjective scales/questionnaires, ISO

10551 [10]. A further problem is that many researchers use parts of many different standards; there is no complete standard for outdoor thermal comfort surveys.

There is thus an obvious need for standardization and to give guidance regarding how to perform field surveys in outdoor environments. This review has concluded that there is a need to:

- Give guidance on the experimental design
- Standardize micrometeorological instruments and measurement methods
- Standardize questionnaires regarding subjective thermal perception and personal information.
- Recommend suitable thermal comfort indices to assess thermal comfort
- Standardize reporting of outdoor thermal comfort studies

The guidance on the experimental design should include site selection, season and time period of the survey, number subjects to interview, etc.

As regards standardization of instruments and measurement methods a limited number of methods to determine T_{mrt} should be standardized, including the popular and cost effective globe thermometer. This instrument should be standardized as regards shape, size, material, colour and type of temperature sensor. Similarly wind measurements should be standardized as regards required accuracy and response time and suitable instruments should be recommended. The shielding and ventilation of the air temperature (and humidity) probe is crucial for correct measurement outdoors and minimum requirements should also be standardized.

As regards questionnaire design, a standardization of subjective judgement scales suitable for outdoor thermal comfort studies would be beneficial. This should include appropriate scales for thermal perception, thermal preference, acceptability, etc., both as regards number of answering alternatives and wording. The standard should also give guidance on statistical analysis of survey data.

A future standard or guideline should also recommend suitable thermal comfort indices – depending on the aim of the study – as well as guidance on how to calibrate these indices based on objective measurements/calculations and subjective responses on thermal perception.

Finally, it would be appropriate to standardize the reporting of outdoor thermal comfort surveys. This could include minimum requirements on the description of the measurement sites and their surroundings, description on measurement methods (positioning of instruments, type and accuracy of instruments), choice of thermal comfort index (if any), questionnaire design, etc.

Wider participation in the development of standardization process will ensure wider acceptance and deployment by the research community. A possible first step could be the creation of an international working group or committee, e.g. within the International Association of Urban Climate (www.urban-climate.org).

References

[1] RUROS: Rediscovering the Urban Realm and Open Spaces. M. Nikolopoulou (Project Coordinator). http://alpha.cres.gr/ruros/ (accessed 14 December 2012)

[2] M. Nikolopoulou, S. Lykoudis, Thermal comfort in outdoor urban spaces: Analysis across different European countries, Build. Environ. 41 (2006) 1455–1470.

[3] N. Kántor, J. Unger, Á. Gulyás, Subjective estimation of thermal environment in recreational urban spaces – Part 2: international comparison, Int. J. Biometeorol. 56 (2012) 1089-1101.

[4] ASHRAE 55, Thermal Environmental Conditions for Human Occupancy, ASHRAE, Atlanta (GA), 2010

[5] ASHRAE, Handbook of Fundamentals. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2001.

[6] ISO 7726, Ergonomics of the thermal environment – Instruments for measuring physical quantities, International Organization for Standardization, Geneva, 1998.

[7] ISO 7730, Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, International Organization for Standardization, Geneva, 2005.

[8] ISO 8996, Ergonomics of the thermal environment – Determination of metabolic rate, International Organization for Standardization, Geneva, 2004.

[9] ISO 9920, Ergonomics of the thermal environment – Estimation of thermal insulation and water vapour resistance of a clothing ensemble, International Organization for Standardization, Geneva, 2007.

[10] ISO 10551, Ergonomics of the thermal environment – Assessment of the influence of the thermal environment using subjective judgement scales, International Organization for Standardization, Geneva, 1995.

[11] VDI 3787 Part 2, Environmental meteorology – Methods for the human biometeorological evaluation of climate and air quality for urban and regional planning at regional level; Part I: Climate, Beuth Verlag , Berlin, 2008.

[12] WMO-No. 8, Guide to Meteorological Instruments and Methods of Observation, WMO-No. 8, Seventh edition, 2008, World Meteorological Organization (WMO)

[13] I.D. Stewart, T.R. Oke, Local Climate Zones (LCZ) for urban temperature studies. Bull. Am. Met. Soc. 93 (2012) 1879–1900.

[14] H. Mayer, P. Höppe, Thermal comfort of man in different urban environments, Theor. Appl. Climatol. 38 (1987) 43-49.

[15] S. Thorsson, F. Lindberg, I. Eliasson and B. Holmer, Different methods for estimating the mean radiant temperature in an outdoor urban setting, Int. J. Climatol. 27 (2007) 1983-1893.

[16] J. Spagnolo, R. de Dear, A field study of the thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. Build. Environ. 38 (2003) 721–738.

[17] S. Thorsson, T. Honjo, F. Lindberg, I. Eliasson, E.M. Lim, Thermal comfort and outdoor activity in Japanese urban public places, Environ. Behav. 39 (2007) 660-684.

[18] M.W. Yahia, E. Johansson, Evaluating the behaviour of different thermal indices by investigating various outdoor urban environments in the hot dry city of Damascus, Syria, Int. J. Biometeorol. 57 (2013) 615–630. Doi: 10.1007/s00484-012-0589-8.

[19] M. Nikolopoulou, N. Baker, K. Steemers, Improvements to the globe thermometer for outdoor use, Arch. Sci. Rev. 42 (1999) 27–34. Doi: 10.1080/00038628.1999.9696845

[20] B.W. Olesen, J. Rosendahl, L.N. Kalisperis, L.H. Summers, P.E. Steinman, Methods for measuring and evaluating the thermal radiation in a room. ASHRAE Transactions 95 (1989) 1028–1044

[21] A. Matzarakis, F. Rutz, H. Mayer, Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. Int J Biometeorol 54 (2010) 131–139.

[22] F. Lindberg, B. Holmer, S. Thorsson, SOLWEIG 1.0 – Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. International Journal of Biometeorology 52 (2008) 697–713.

[23] M. Bruse, (2011). *ENVI-met Model Homepage*. http://www.envi-met.com. (accessed 14 December 2012).

[24] M. Nikolopoulou, K. Steemers, Thermal comfort and psychological adaptation as a guide for designing urban spaces, Energy Build. 35 (2003) 95–101

[25] I. Knez, S. Thorsson, I. Eliasson, F. Lindberg, Psychological mechanisms in outdoor place and weather assessment: Towards a conceptual model, Int. J. Biometeorol. 53 (2009) 101-111. Doi: 10.1007/s00484-008-0194-z

[26] I. Knez, S. Thorsson, Influences of culture and environmental attitude on thermal, emotional and perceptual evaluations of a public square. Int J Biometeorol 50 (2006) 258–268. Doi: 10.1007/s00484-006-0024-0

[27] I. Knez, S. Thorsson, Thermal, emotional and perceptual evaluations of a park: Cross-cultural and environmental attitude comparisons, Build. Environ. 43 (2008) 1483–1490.

[28] K. Blazejczyk, Y. Epstein, G. Jendritzky, H. Staiger, B. Tinz, Comparison of UTCI to selected thermal indices, Int J Biometeorol 56 (2012) 515–535. Doi: 10.1007/s00484-011-0453-2

[29] D.A. McIntyre, Indoor Climate, London, Applied Science Publishers, 1980.

[30] P. Höppe, The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment, Int. J. Biometeorol. 43 (1999) 71-75.

[31] G. Havenith, D. Fiala, K. Blazejczyk, M. Richards, P. Bröde, I. Holmér, H. Rintamaki, Y. Benshabat, G. Jendritzky, The UTCI-clothing model. Int J Biometeorol. 56 (2011) 461-470. Doi:10.1007/s00484-011-0451-4

[32] B. Givoni, M. Noguchi, H. Saaroni, O. Potchter, Y. Yaacov, N. Feller, S. Becker, Outdoor comfort research issues, Energy Build. 35 (2003) 77–86.

[33] N. Metje, M. Sterling, C.J. Baker, Pedestrian comfort using clothing values and body temperatures, J. Wind Eng. Ind. Aerodyn. 96 (2008) 412–435.

[34] E.L. Krüger, F.A. Rossi, Effect of personal and microclimatic variables on observed thermal sensation from a field study in southern Brazil. Build. Environ. 46 (2011) 690-697.

[35] M. Nikolopoulou, Outdoor thermal comfort, Frontiers in Bioscience S3 (2011) 1552–1568. Doi: 10.2741/245

[36] P. Bröde, E.L. Krüger, F.A Rossi, D. Faila, Predicting urban outdoor thermal comfort by the Universal Thermal climate index UTCI – a case study in Brazil, Int. J. Biometeorol. 56 (2012) 471-480. Doi 10.1007/s00484-011-0452-3

[37] T. Stathopoulos, H. Wu, J. Zacharias, Outdoor human comfort in an urban climate, Build. Environ. 39 (2004) 297–305.

[38] T. Xi, Q. Li, A. Mochida, Q. Meng, Study on the outdoor thermal environment and thermal comfort around campus clusters in subtropical urban areas, Build. Environ. 52 (2012) 162-170. doi: 10.1016/j.buildenv.2011.11.006.

[39] E. Ng, V. Cheng, Urban human thermal comfort in hot and humid Hong Kong, Energy Build. 55 (2012) 51–65. Doi: 10.1016/j.enbuild.2011.09.025

[40] V. Cheng, E. Ng, C. Chan, B. Givoni, Outdoor thermal comfort study in a sub-tropical climate: a longitudinal study based in Hong Kong, Int. J. Biometeorol. 56 (2012) 43-56. Doi: 10.1007/s00484-010-0396-z

[41] J.F Yin, Y.F. Zheng, R.J. Wu, J.G. Tan, D.X. Ye, W. Wang, An analysis of influential factors on outdoor thermal comfort in summer, Int. J. Biometeorol. 56 (2012) 941–948.

[42] A.H.A. Mahmoud, Analysis of the microclimatic and human comfort conditions in an urban park in hot and arid regions, Build. Environ. 46 (2011) 2641–2656.

[43] N. Kántor, L. Égerházi, J. Unger, Subjective estimation of thermal environment in recreational urban spaces – Part 1: investigations in Szeged, Hungary, Int. J. Biometeorol. 56 (2012) 1075–1088.

[44] S. Becker, O. Potchter, Y. Yaacov, Calculated and observed human thermal sensation in an extremely hot and dry climate, Energy Build. 35 (2003) 747–756.

[45] N. Makaremi, E. Salleh, M.Z. Jaafar, A.H.G. Hoseini, Thermal comfort conditions of shaded outdoor spaces in hot and humid climate of Malaysia, Build. Environ. 48 (2012) 7-14. Doi: 10.1016/j.enbuild.2011.07.024

[46] S. Oliveira, H. Andrade, An initial assessment of the bioclimatic comfort in an outdoor public space in Lisbon, Int. J. Biometeorol. 52 (2007) 69–84.

[47] H. Andrade, M.J. Alcoforado, S. Oliveira, Perception of temperature and wind by users of public outdoor spaces: relationships with weather parameters and personal characteristics. Int. J. Biometeorol. 55 (2011) 665-680. Doi: 10.1007/s00484-010-0379-0

[48] W. Yang, N.H. Wong, S.K. Jusuf, Thermal comfort in outdoor urban spaces in Singapore, Build. Environ. 59 (2013) 426–435. Doi: 10.1016/j.buildenv.2012.09.008.

[49] S. Thorsson, M. Lindqvist, S. Lindqvist, Thermal bioclimatic conditions and patterns of behavior in an urban park in Göteborg, Sweden, Int. J. Biometeorol. 48 (2004) 149–156.

[50] I. Eliasson, I. Knez, U. Westerberg, S. Thorsson, F. Lindberg, Climate and behavior in a Nordic city, Landsc. Urban Plan. 82 (2007) 72-84. Doi: 10.1016/j.landurbplan.2007.01.020

[51] T.-P. Lin, R. de Dear, R.L. Hwang, Effect of thermal adaptation on seasonal outdoor thermal comfort, Int. J. Climatol. 31 (2011) 302–312.

[52] T.-P. Lin, Thermal perception, adaptation and attendance in a public square in hot and humid regions, Build. Environ. 44 (2009) 2017-2026.

[53] M. Nikolopoulou, N. Baker, K. Steemers, Thermal comfort in outdoor urban spaces: understanding the human parameter, Sol. Energy 70 (2001) 227–235.

[54] E. Krüger, P. Drach, R. Emmanuel and O. Corbella, Urban heat island and differences in outdoor comfort levels in Glasgow, UK, Theor. Appl. Climatol. 112 (2013) 127–141. Doi: 10.1007/s00704-012-0724-9.

[55] R.M. Libert, L.L. Libert 1995, Science and behavior: an introduction to methods of psychological research. Prentice Hall, New York, 1995.

[56] P. Höppe, Different aspects of assessing indoor and outdoor thermal comfort, Energy Build. 34 (2002) 661-665.

Table 1: Topics covered by different standards, guidelines and handbooks [4-11].

Topic	ASHRAE 55	ASHRAE Handbook	ISO 7726	ISO 7730	ISO 8996	ISO 9920	ISO 10551	VDI 3787
Instruments								
Type of instruments		X	X					
Required measuring range, accuracy and response time			X					
Determination of the mean radiant temperature		X	X					X
Assessment of thermal comfort								
Thermal comfort indices	X	X		X				X
Requirements on thermal comfort	X	X		X				X
Activity levels/metabolic rate	X	X		X	X			X
Clothing insulation	X	X		X		X		X
Questionnaire design								
Subjective scales	X						X	
Statistical evaluation							X	

Table 2: Requirements on measuring range and accuracy for instruments for comfortable and stressful environments according to the international standard ISO 7726:1998 [6].

Measured parameter	Thermal environment	Measuring range	Accuracy Required	 Desirable
Air temperature	Comfort	+10 to +40 °C	± 0.5 °C	± 0.2 °C
	Stress	–40 to +120 °C	– 40 °C: ± 0.9 °C 0 to + 50 °C: ± 0.5 °C + 120 °C: ± 3.3 °C	± 0.45 °C ± 0.25 °C ± 1.65 °C
Mean radiant temperature	Comfort	+10 to +40 °C	± 2 °C	± 0.2 °C
	Stress	–40 to +150 °C	– 40 °C: ± 5.8 °C 0 to + 50 °C: ± 5 °C + 150 °C: ± 13 °C	± 0.9 °C ± 0.5 °C ± 4.5 °C
Air velocity	Comfort	0.05 to 1 m/s	± (0.05 + 0.05 v_a) m/s	± (0.02 + 0.07 v_a) m/s
	Stress	0.2 to 20 m/s	± (0.1 + 0.05 v_a) m/s	± (0.05 + 0.05 v_a) m/s
Absolute humidity	Comfort	0.5 to 3.0 kPa	±0.15 kPa	
	Stress	0.5 to 6.0 kPa	±0.15 kPa	

Table 3: Protocols for the subjective perception of thermal environments.

Parameter of thermal state	Standard	Interview Question	Measurement scale
Thermal perception	ISO 10551 [10]	'How are you feeling now?'	7 point scale: Cold (–3), Cool (–2), Slightly cool (–1), Neutral (0), Slightly warm (+1), Warm (+2) and Hot (+3) or 9-point scale: above plus 'Very cold' (–4) and 'Very hot' (+4) (mainly for use in extreme environments)
	ASHRAE 55 [4]	'What is your general thermal sensation?'	7-point symmetrical thermal perception scale (equal in wording to the ISO 10551) (often referred to as the 7-point ASHRAE scale)
Thermal comfort (affective evaluation)	ISO 10551 [10]	'Do you find this environment…?'	4-point: Comfortable (0) as the point of origin followed by Slightly uncomfortable (1), Uncomfortable (2), Very uncomfortable (3); 5-point: above plus Extremely uncomfortable (4)
Thermal preference	ISO 10551 [10]	'Please state how you would prefer it to be now'	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).
	McIntyre [29]	'Would like it to be …?'	3-point: Cooler (–1), No change (0) and Warmer (+1)
Personal acceptability	ISO 10551 [10]	'On a personal level, this environment is for me …'	Two-category statement: Acceptable rather than unacceptable (0) and Unacceptable rather than acceptable (1) or Continuous scale: Clearly acceptable, Just acceptable, Just unacceptable and Clearly unacceptable
	ASHRAE 55 [4]	'How satisfied are you with the temperature in your space?'	7-point: Very satisfied (+3) and Very dissatisfied (–3) with neutral (0) in the middle (votes from 0 to +3 are considered acceptable)
Personal tolerance	ISO 10551 [10]	'Is it …?'5-point:	5-point: Perfectly tolerable (0), Slightly difficult to tolerate (1), Fairly difficult to tolerate (2), Very difficult to tolerate (3) and Intolerable (4)

Table 4: Common rational thermal comfort indices that have been used in outdoor thermal comfort studies

Index	Key references	Description
Predicted Mean Vote (PMV)	[4,5,7,28,29]	Mainly for indoors; include all the meteorological variables that affect thermal comfort (air temperature, air humidity, wind speed and mean radiant temperature) as well as personal variables (clothing and activity)
Standard Effective Temperature (SET*)	[5,28,29]	
Effective Temperature (ET*)	[5,28,29]	Mainly for indoors; only takes the four meteorological variables into account, whereas clothing and activity are standardised for indoor sedentary.
Perceived Temperature (PT)	[11,28]	Based on the PMV equation, but can be used for outdoors
Physiologically Equivalent Temperature (PET)	[11,28,30]	Intended for outdoors; only uses four variables as ET*; clothing and activity are standardised for indoor sedentary.
Universal Thermal Climate Index (UTCI)	[28,31]	No information on the clothing insulation level of the surveyed population is required. Reference condition for activity: metabolic rate of 135 W/m^2 and a walking speed of 1.1 m/s

Table 5: Countries and cities of the compared studies where field campaigns have taken place. Climate zones are according to Köppen's climate classification. Geographical data come from the studied articles, http://koeppen-geiger.vu-wien.ac.at/present.htm and Google Earth

Country	City	Climate (Köppen classification)	Climate symbol	Latitude	Longitude	Altitude (m)	Year published	Study
Australia	Sydney	Humid subtropical	Cfa	33.9° S	151.2° E	19	2003	[16]
Brazil	Curitiba	Mesothermic, humid subtropical	Cfb	25.5° S	49.2° W	926	2011	[34]
							2012	[36]
Canada	Montreal	Humid continental, mild summer	Dfb	45.5° N	73.5° W	30	2004	[37]
China	Guangzhou	Humid subtropical	Cfa	23.1° N	113.3° E	5	2012	[38]
	Hong Kong	Humid subtropical	Cwa	22.3° N	114.2° E	142	2012	[39]
							2012	[40]
	Nanjing	Humid subtropical	Cfa	32.0° N	118.8° E	30	2012	[41]
Egypt	Cairo	Desert arid	BWh	31.0° N	31.3° E	~50	2011	[42]
Germany	Kassel	Maritime temperate (Oceanic)	Cfb	51.3° N	9.5° E	178	2006	[2]
Greece	Athens	Mediterranean	Csa	38.0° N	23.7° E	70	2006	[2]
	Thessaloniki	Humid subtropical	Cfa	40.6° N	22.9° E	44	2006	[2]
Hungary	Szeged	Maritime	Cfb	46.3° N	20.1° E	77	2012	[43]

		temperate (Oceanic)						
Israel	Yotvata	Desert arid	BWh	29.6° N	34.9° E	86	2003	[44]
Italy	Milan	Maritime temperate (Oceanic)	Cfb	45.5° N	9.2° E	122	2006	[2]
Japan	Matsudo	Humid subtropical	Cfa	35.8° N	139.9° E	9	2007	[17]
	Yokohama	Humid subtropical	Cfa	35.4° N	139.6° E	11	2003	[32]
Malaysia	Putrajaya	Tropical rainforest	Af	2.9° N	101.7° E	45	2012	[45]
Portugal	Lisbon	Mediterranean	Csa	38.7° N	9.2° W	84	2007	[46]
							2011	[47]
Singapore	Singapore	Tropical rainforest	Af	1.4° N	103.7° E	5	2013	[48]
Sweden	Gothenburg	Maritime temperate (Oceanic)	Cfb	57.7° N	12.0° E	36	2004	[49]
							2007	[50]
Switzerland	Fribourg	Maritime temperate (Oceanic)	Cfb	46.8° N	7.0° E	646	2006	[2]
Syria	Damascus	Dry, steppe	BSk	33.6° N	36.3° E	689	2013	[18]
Taiwan	Chiayi	Humid subtropical	Cwa	23.3° N	120.4° E	252	2011	[51]
	Taichung	Humid subtropical	Cwa	24.1° N	120.7° E	26	2009	[52]
							2011	[51]
	Yunlin	Humid	Cwa	23.7° N	120.5° E	18	2011	[51]

		subtropical						
United Kingdom	Birmingham	Maritime temperate (Oceanic)	Cfb	52.5° N	1.9° W	127	2008	[31]
	Cambridge	Maritime temperate (Oceanic)	Cfb	52.2° N	0.1° E	17	2001	[53]
	Glasgow	Maritime temperate (Oceanic)	Cfb	55.9° N	4.3° W	31	2006 2013	[2] [54]
	Sheffield	Maritime temperate (Oceanic)	Cfb	53.4° N	1.5° W	97	2006	[2]

Table 6: Methodological aspects analysed by the present study

Methodological aspects studied	Details
Experimental design	Seasons of the year; Time of day of survey; Type of urban environment; Method of documenting site
Meteorological measurements	Meteorological variables measured; Instrumentation set-up (including type of equipment and accuracy); Methods to determine Tmrt
Questionnaire design	Number of subjects interviewed; Demographic and personal information about the subjects; Questions related to thermal comfort and thermophysiological stress (including type of scales used for thermal perception, thermal comfort, thermal preference as well as acceptability and tolerance); Psychological mechanisms involved in outdoor place; Comparison of thermal comfort assessment
Thermal indices, assessment of the thermal environment	Types of index used to determine thermal comfort; Grades of thermophysiological stress; Whether thermal comfort indices were calibrated against the subjective thermal perception votes (i.e. determination of thermal comfort limits); Whether neutral temperature and preferred (index) temperature were determined

Table 7: Number of subjects interviewed in the different studies.

City	Season	Time of day	No. of votes	Study
Athens, Cambridge, Fribourg, Kassel, Milan, Sheffield, Thessaloniki	Summer, autumn, winter, spring	Morning, midday, afternoon, evening	9189[e]	[2]
Birmingham, UK	Aug. – Feb.	Afternoon	451	[33]
Cairo, Egypt	Summer, winter	Afternoon	300	[42]
Cambridge, UK	Summer, autumn, winter, spring	Midday	1431	[53]
Curitiba, Brazil	Jan. – Aug.	Morning to afternoon	1654	[34,36]
Damascus, Syria	Summer, winter	Morning, afternoon	920	[18]
Glasgow, UK	March to July	Morning to afternoon	567	[54]
Gothenburg, Sweden	July to October	Afternoon	285	[49]
Gothenburg, Sweden	Oct., Jan., Apr. & June	Morning, afternoon	1379	[50]
Guangzhou, China	July	Daytime	114[a]	[38]
Hong Kong	Summer, winter	Morning, afternoon, evening	2702	[39]
Hong Kong	Summer, winter	Morning, afternoon, evening	286[b]	[40]
Lisbon, Portugal	March, April	Afternoon	91	[46]
Lisbon, Portugal	All year	Afternoon	943	[47]
Matsudo, Japan	March, May	Morning to afternoon	1142	[17]
Montreal, Canada	Spring, autumn	Midday (noontime)	466	[37]
Nanjing, China	August	Whole day	205	[41]
Putra, Malaysia	March – April	Morning, afternoon	200	[45]
Singapore	Aug. – May	Morning, afternoon, evening	2036	[48]
Sydney, Australia	All year	Not specified	1018	[16]
Szeged, Hungary	Autumn, spring	Afternoon	967	[43]
Taichung, Taiwan	All year	Afternoon	505	[52]
Taichung, Yunlin, Chiayi, Taiwan	Winter to summer	Not specified	1644	[51]
Yokohama, Japan	All seasons	Ear. morning to late afternoon	1134[d]	[32]
Yotvata, Israel	July	24 hours	~100[c]	[44]

[a] A group of 21 students

[b] A group of 8 persons

[c] A group of 36 students

[d] A group of 6 persons

[e] Total for seven cities

Table 8: Ways to measure and/ or model the mean radiant temperature (Tmrt) in the reviewed studies. Two studies [17,50] combined two methods.

Measurements	No. of studies	Studies
Globe temperature, air temperature, wind speed	12	[2,18,34/36,38-40,17,45,48,51,53,54]
Incoming short- and longwave radiation from six directions	3	[43,46,47]
Incoming shortwave (direct, diffuse and reflected) and longwave radiation from two directions	1	[16]
Incoming global shortwave radiation and modelling with RayMan	5	[42,17,49,51,52]
Tmrt calculated from global radiation and ground surface temperature	1	[44]
No calculation of Tmrt	5	[32,33,37,41,50]

Table 9: Types of globe thermometer used.

Brand	Globe material	Diam. (mm)	Sensor	Colour	No. of studies	Studies
Taylor made	Celluloid	38/40[a]	Pt100	Grey	2	[17,18]
Taylor made	Celluloid	38	Testo thermocouple	Black	2	[39,40]
Hobo S-TMA-M002	Copper	51	Not specified	Grey	1	[34,36][b]
Taylor made	Not specified	110	TinyTag TGP-4500	Grey	1	[54]
Taylor made	Not specified	Not specified	Pt100	Grey	1	[2]
GL-200 & Globe ball	Not specified	150	Not specified	Not specified	1	[38]
Delta Ohm TP3276.2	Not specified	Not specified	Not specified	Not specified	1	[45]
Not specified	Not specified	Not specified	Not specified	Not specified	3	[48,51,53][c]

[a] The diameter of a table tennis ball was originally 38 mm but the standard since the year 2000 is 40 mm.

[b] Two articles from the same study

[c] In two studies [51,52] the globe thermometer was reported to fulfil the requirements of ISO 7726 [6]

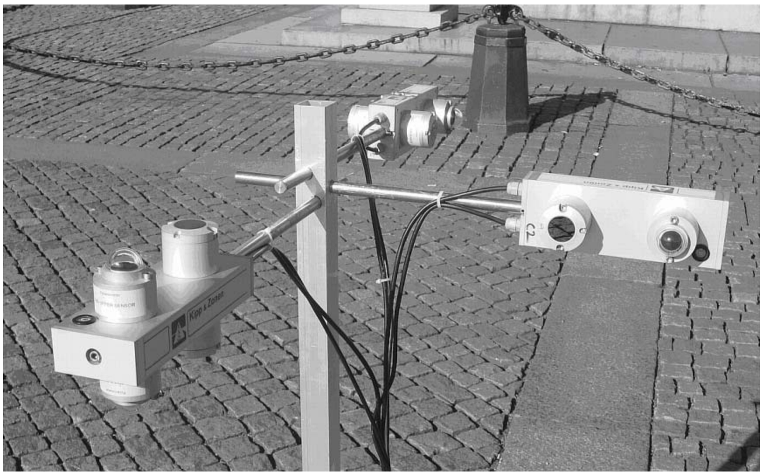

Fig 1

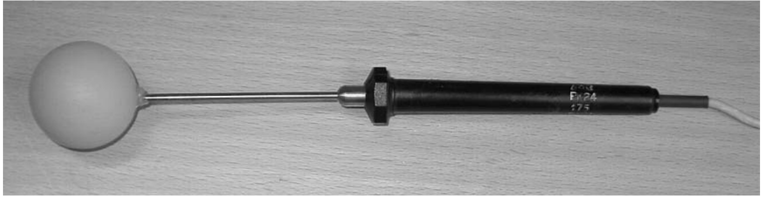

Fig 2

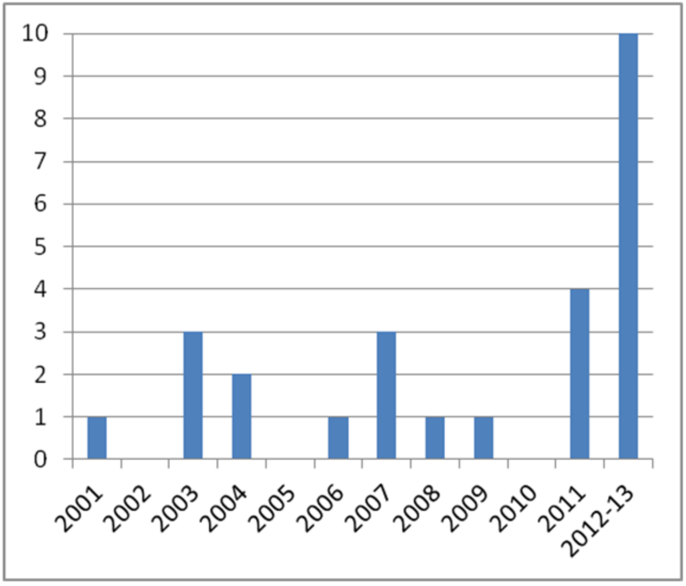

Fig 3

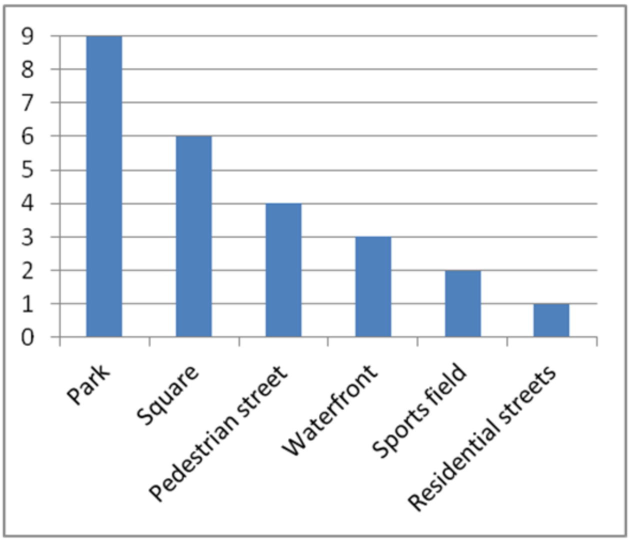

Fig 4

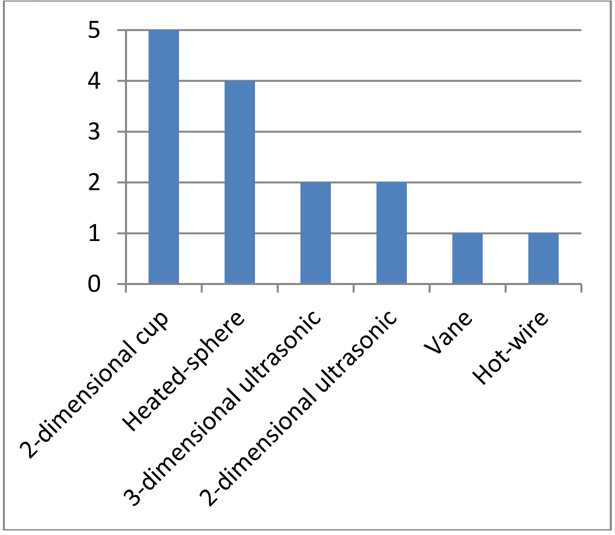

Fig 5

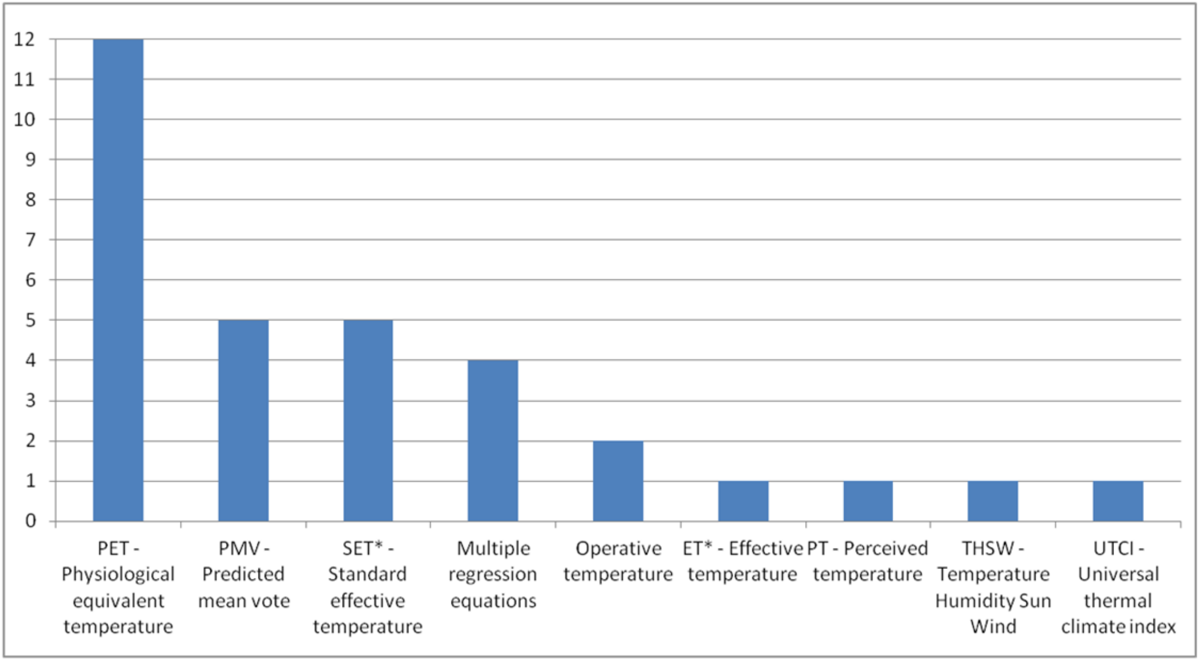

Fig 6