International Journal of Biometeorology (2020) 64:253–264
https://doi.org/10.1007/s00484-019-01708-y

SPECIAL ISSUE: SUBJECTIVE APPROACHES TO THERMAL PERCEPTION

Semantics of outdoor thermal comfort in religious squares of composite climate: New Delhi, India

S. Manavvi[1] · E. Rajasekar[1]

Received: 3 November 2017 / Revised: 6 January 2019 / Accepted: 5 March 2019 / Published online: 27 March 2019

Abstract

Religious spaces are an integral part of Indian cities. Unique in their spatiality, they function as socio-cultural hubs drawing users from varied economic and social hierarchies. This study deals with physical and perceptional assessments of micrometeorological conditions in two religious squares namely Hanuman Mandir Square (HMS) and Gurudwara Bangla Sahib Square (GBS) located in New Delhi (28.6° N; 77.2° E), India. The study involved real-time physical measurement of environmental variables such as dry-bulb temperature (T_a, °C), globe temperature (T_g, °C), relative humidity (RH), and air velocity (V_a). Variables such as physiological effective temperature (PET), universal thermal comfort index (UTCI), and mean radiant temperature (T_{mrt}, °C) were computed from measured variables. Concurrent thermal comfort surveys were carried out with 353 respondents in both the squares. The paper describes the thermal characteristics of the studied squares and presents the associated subjective thermal response and preferences of the users. PET was found to correlate well with the subjective responses. The neutral value of PET is found to be 24.7 °C. The neutral PET value of respondents visiting for non-worship purposes was found to be 2.7 °C lesser than those visiting for worship purposes. People visiting the squares for non-worship purpose however were found to be more tolerant of higher PET conditions as compared to others. Factors such as intent of visit, solar exposure, thermal history, and landscape elements were found to have a statistically significant influence on the thermal perception. The paper further summarizes the adaptive opportunities preferred by the users in order to improve thermal comfort in the studied squares. A weighted ranking of adaptive preferences reported by the respondents has also been presented.

Introduction

Climate-responsive design of urban open spaces is assuming vital significance today in view of the escalating heat stress in cities. However, thermal comfort outdoors has received relatively lesser research attention as compared to the indoors. Numerous studies on human thermal environments since early 1920 (Houghten and Yaglou 1923) have led to the formulation of indoor thermal comfort indices such as the PMV (Fanger, 1972), new effective temperature, and standard effective temperature (Gagge et al. 1986). Most of the thermal indices approached comfort as a thermo-physiological phenomenon. ASHRAE (2010) however defines thermal comfort as the condition of the mind, which expresses satisfaction with the thermal environment. An entirely thermo-physiological approach is seemingly insufficient to explain comfort entirely. Thermal comfort research since 1970s therefore witnessed a paradigm shift in approach from thermal physiology towards human adaptation based on the seminal work of Humphreys (1970). With respect to outdoor thermal comfort, on the other hand, indices such as wind chill index (Siple and Passel 1945) and temperature humidity index (Thom 1959) have been widely used. Biometeorological indices such as physiological equivalent temperature (PET) (Mayer and Höppe 1987) and universal thermal comfort index (UTCI) (Höppe 2002) are being field validated globally since the last decade (Nikolopoulou 2011). Taking cue from the work of Rohles (1980), Auliciems (1981) researchers have begun focusing on thermal perception and psychological influences shaping thermal experiences outdoors. Studies have established that understanding of psychological, social, and spatial construct is crucial to comprehend thermal comfort outdoors (Zacharias

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00484-019-01708-y) contains supplementary material, which is available to authorized users.

✉ S. Manavvi
ar.la.manavi@gmail.com

[1] Department of Architecture and Planning, Indian Institute of Technology, Roorkee, India

et al. 2001; Ahmed 2003; Knez and Thorsson 2006; Lin 2009;Tseliou et al., 2010; Lin et al. 2011; Monteiro and Alucci 2012; Ng and Cheng 2012; Nikolopoulou 2011; Yahia and Johansson 2013; Krüger et al. 2017; Johansson et al. 2018). Nikolopoulou et al. (2006) provided the theoretical framework for thermal adaptation in the outdoor context. The role of contextual and geographical factors—culture and the climate that people are adapted to was highlighted by Knez and Thorsson (2006), Knez et al. (2009), and Aljawabra and Nikolopoulou (2010). In parallel, studies in environmental psychology focused on understanding attributes that influence user preference for urban open spaces (e.g., Herzog et al. 1976; Herzog 1992). Spatial characteristics such as enclosure, building configuration, vegetation, and color palette of materials used were found to influence human sensory experience and behavioral response (Herzog et al. 1976; Herzog 1992; Lindal and Hartig 2013; Smardon 1988). The above studies suggest the seminal role of the designer in articulating experience of users in outdoor spaces. In order to design thermally comfortable urban open spaces, it is imperative for designers to understand how spatial characteristics shape thermal experience and preferences. Researchers have thus begun focusing on perception driven and evidence based design of varied urban spaces such as squares, parks, and streets through adoption of unique methodologies (e.g., Lenzholzer et al., 2010; Klemm et al. 2015; Vasilikou, 2015; Krüger et al. 2017).

There is a lack of information on thermal comfort conditions in different outdoor spaces in India (Ali and Patnaik 2017). Most of the research is focusing on urbanization led environmental problems at the macroscale. However, knowledge of thermal comfort conditions prevailing in open spaces at the microscale is equally crucial for urban planners and designers to plan better. In an attempt to bridge the gap, this study investigated the thermal comfort conditions in outdoor spaces associated with religious precincts. Religious precincts offered a unique context for such a study. Associated with a distinct temporality, rituals, and overlapping activities, they function as public gathering spots in the city fabric. They are vibrant sites of public engagement, community interaction, and enjoy good footfall.

In light of the above, the study hypothesized that context plays a pivotal role in thermal perception outdoors and therefore the perceived thermal comfort conditions, thermal acceptability, and thermal adaptation in religious squares would be different. The objectives of the study were (a) to investigate the physical and perceived micrometeorological conditions of outdoor spaces associated with religious precincts during typical summer days (b) to identify the significant factors affecting thermal perception and adaptation in these spaces, and (c) to determine and rank the measures that can be adopted to improve thermal acceptability in these spaces.

Materials and methods

Study area

As per the national building code of India, New Delhi (28.6° N, 77.2° E) is characterized by a composite climate. The temperature during intense hot summers reaches to 44 °C (mean maximum being 40.3 °C). Winters are typically cold; with temperature plummeting as low as 1 °C (mean minimum being 18.7 °C). The city receives 75% of the rainfall during the monsoon months of July, August, and September. The solar radiation varies from 326 to 704 W/m ^{2}/day throughout the year.

Location of study

The study was conducted in two religious squares. Both the squares chosen for the study have been designed unlike other spontaneous developments associated with the religious precincts. One of them is associated with the Hanuman Mandir Square (HMS), and the other is associated with Gurudwara Bangla Sahib (GBS). Located approximately 700 m apart, the chosen squares lie on either ends of the Baba Khark Singh Marg—a significant radial road that originates from Connaught Place and culminates at the Talkatora Road (refer to Supplementary material A1). Unique in their spatiality, these squares embody the quintessential Indian public space with overlapping activities pertaining to shopping, congregation, and worship.

HMS experiences a footfall of about 1500 people/day typically and exceeds 2000 people/day on ceremonious occasions. Tuesdays and Saturdays are particular days of worship of lord Hanuman. Schematically, the square comprises of three distinct zones—the main entry cum congregation zone, the rear zone flanked by the food court, and an outdoor shopping zone (refer to Supplementary material A1). It houses a small market place selling religious offerings, flowers, and traditional Indian crafts. HMS is characterized by interplay of levels, a varying material palette including granite (red, gray, and black), tiles, and cobblestone. It is dotted with old *Ficus religiosa* and *Prosopius juliflora* trees. GBS on the other hand constitutes the main and busiest pedestrian entry to the Gurudwara Bangla Sahib. It experiences a footfall of 600 to 1100 people/day. Sunday is considered as a special day. GBS is frequented by devotees and passerby alike. It is predominantly hard paved with white and black marble patterns, houses a fountain, and is characterized by absence of trees (refer to Supplementary material A1). Unlike HMS, GBS does not have any provision for shopping within the premises. Shops selling religious offerings however are located on the footpath flanking the Baba Kharak Singh Marg itself.

Conduct of study

The study was conducted for 5 days (June 10–14, 2017) between 11:00 and 18:00 h. The study period is typically representative of the summer season, characterized by high solar radiation, clear sky, and calm conditions. Table 1 illustrates the meteorological conditions prevalent during the study as obtained from meteorological department. The meteorological conditions during the survey days were comparable, the average temperature being 33.8 °C ($\sigma = 1$ °C), average humidity being 30.86% ($\sigma = 2.9\%$), and average solar radiation being 620 W/m^2; the measured micrometeorological conditions recorded at the sample locations and the details of subjective interviews conducted at a given location are presented in Table 1.

Figure 1 presents a snapshot of locations where the measurements were recorded. The locations were sampled to represent maximum diversity in physical characteristics, solar exposure, activity associated, and footfall, as investigated through a pilot study. A total of eight locations were sampled, and they were abbreviated as location followed by day of study (e.g., HMS_MEH_1).

Micrometeorological measurements

The micrometeorological parameters investigated in the study include air temperature (T_a, °C), relative humidity (RH, %), globe temperature (T_g, °C), and wind speed (WS, m/s). A time series measurement at an interval of 5 min was made during the study period. The details of instruments used in the study are presented in T1 (refer to Supplementary material). The instruments were mounted on a tripod at the height of 1.2 m. Sensors used in the study were factory calibrated and a consistency check among the different sensors was performed before deployment. The measurements corresponded to Class II field study protocols (ISO 7730 2005). The sky view factor for the study locations was computed from fish-eye images captured at the sampled locations. Table 2 lists the key attributes of the sampled locations.

Thermal comfort assessment

The micrometeorological measurements at the study locations were accompanied by concurrent transverse subjective surveys conducted using an Android based mobile application developed by the authors (refer to Supplementary material A2). The bilingual questionnaire (English and Hindi) comprised of 25 questions (refer to Supplementary material A3). The questionnaire was divided into four parts. Part A assessed the respondents' thermal sensation, thermal acceptability and thermal preference. Thermal sensation vote (TSV) was recorded on a 7-point ASHRAE scale ("− 3" = very cold; "− 2" = cold; "− 1" = cool; "0" = neutral; "1" = warm "2" = hot;

Table 1 Comparison of measured and weather station data for study period

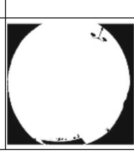
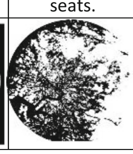
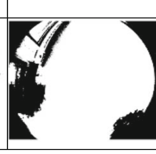
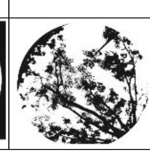
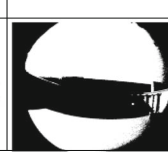
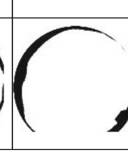
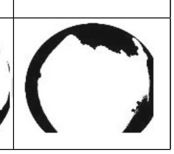
Date	Site name (abbreviate)	Number of interviews	Average (T_a, °C) weather station data	Average Rh (%) weather station data	Average (T_a, °C) micrometeorological data	Average (RH%) micrometeorological data	Average (V m/s) micrometeorological data
June 10, 2017	GBS_ FOU_1	54	33.00	44.00	38.38	31	0.46
June 10, 2017	HMS_ MEH_1	47			38.32	35	0.54
June 11, 2017	GBS_ENT_2	30	32.00	41.00	37.56	31	0.45
June 11, 2017	HMS_OAT_2	30			37.90	35	0.58
June 12, 2017	GBS_ARCH PL_3	67	34.00	36.00	39.25	27	0.73
June 12, 2017	HMS_ ASTR PL_3	30			39.33	31	0.22
June 13, 2017	HMS_ENT MAIN PL_4	60	34.00	34.00	41.58	28	1.04
June 14, 2017	HMS_ PRA_5	35	35.00	35.00	41.32	30	0.98

Fig. 1 Sampled locations in the religious squares

"3" = very hot). The respondents were asked to indicate their humidity sensation vote (HSV), wind sensation vote (WSV), and sun sensation vote (SSV) on a 5-point scale.

The thermal acceptability (ATV) was recorded on a 2-point acceptability scale (acceptable; unacceptable) and preferred thermal state was recorded on a 3-point

Table 2 Key attributes of sampled locations in HMS and GBS

Site name	GBS_ FOU_1	HMS_ MEH_1	GBS_ENT_2	HMS_OAT_2	GBS_ARCH PL_3	HMS_ ASTR PL_3	HMS_ ENT MAIN PL_4	HMS_ PRA_5
SVF	0.99	0.65	0.79	0.55	0.81	0.97	0.99	0.85
Surface material	White marble; Polished black granite on vertical surfaces	Honed and sandblasted red granite; polished tan brown granite coping on vertical	White marble	Gray granite with honed black granite bands	White marble	Honed and sandblasted red granite	Red granite	Honed and sandblasted red granite
Frequency under shade	Exposed throughout the day	Partially Shaded through the day.	Partial shade to exposed	Shaded through the day.	Partial shade to exposed	Exposed throughout the day	Exposed throughout the day	Exposed throughout the day
Predominant activity	Standing, sitting Relaxing	Sitting, application of henna, shopping.	Sitting, walking, standing	Sitting, chatting, lying down.	Sitting, standing	Sitting, chatting, reading.	Sitting, standing , gathering.	Distribution of prasad, alms to beggars, sitting, chatting.
Available options for thermal adaptation	Water fountain, planter seats	Shae giving trees, proximity to food and beverages, seats.		Shae giving trees, proximity to food and beverages, stepped seating.		Proximity to food and beverage, trees.		Trees dotting periphery and proximity to food and beverage.
Fish Eye images								

McIntyre scale (prefer warmer, no change and cooler). Part B included questions about intended purpose of visit, frequency of visit, time spent, residence time in the city, and activity level (sitting, standing, or walking) during the last 15-min period, etc. Part C questioned respondents on design attributes of the locations and the associated environmental stimuli. These were recorded on a 5-point Likert scale. Part D collected demographic and personal information pertaining to gender, height, and current clothing type. The clothing insulation (clo) values were calculated according to ASHRAE Standard 55 (ASHRAE, 2013), Indraganti et al. (2015). Metabolic rates in Watts per square meter were calculated based on reported activities in the last 15 mins in accordance with (ISO 8996 2004). Three hundred and fifty-three responses were collected in all from both the squares through the subjective survey. The respondents were Indian nationals and overall in good health. Of the sample, 37% of the respondents (130) were women. Forty-eight percent of the respondents interviewed were aged 20–40 years old, 23% of them in the age group of 40–60 years old, and the rest above 60 years old. Surveys were administered with users who were in near stationary or stationary state of movement. The metabolic rate therefore varied between 1 and 1.5 met based on ASHRAE, 2010 (1 met = 58.15 W/m^2). Of the respondents, 49.2% interviewed were those sitting/standing in shade while the remaining were in sun. About half of the respondents were native residents of Delhi and 37% were residents of the city for more than 3 years. Nearly 60% of the respondents were regular visitors to the squares. The primary intent of visit, exposure time of respondents, route followed and usage pattern varied between the two squares users as shown in A4 (refer to Supplementary material).

In HMS, respondents whose primary intent was to visit the shrine typically spent 5–15 min in the square. The activities observed during this duration included procuring Prasad (offerings to deity) and flowers, waiting in queue (if any). The respondents whose primary intent was non-worship spent nearly 20–30 min in the square and were involved in shopping, application of henna, consulting astrologers, etc. In GBS, on the other hand, the time spent by the respondents who had come primarily for worship purpose was less than 10 min. However, respondents who visited the square for non-worship purpose spent nearly 10–15 min. In HMS, the shrine closely associated (nearly 50 m) with the plaza allows people to easily enter indoors (< 1 min exposure assuming walking speed of 1.4 m/s);while in GBS, people have to traverse nearly 150 m to enter the shrine (1–3 min exposure assuming walking speed of 1.4 m/s).

The typical clothing ensemble for men was short-sleeve shirt, long sleeve shirt, trousers, and shoes, which corresponds to a clo value of about 0.6. The typical female clothing included salwar kameez or short-sleeved kurta with trousers and sandals corresponding to 0.7 clo. Salwar kameez with dupatta corresponded to a clo of 0.8 (Indragantiet al, 2016). The most socially and culturally accepted attire the saree was also common among women especially in HMS. The insulation of cotton saris was found to be 0.54 clo, and since a petticoat is always worn with this attire, its clothing insulation of 0.15 clo was added to the clo value (Indraganti 2010). Mean clo value for men was 0.5 while that of women was 0.7. Mean clothing values for female respondents were found to be slightly higher than male respondents in the present study.

Thermal comfort was assessed using physiological equivalent temperature (PET) and UTCI. PET takes into account air temperature, humidity wind speed, and T_{mrt}. It has been commonly used in outdoor thermal comfort studies and allows for comparison of results with previous studies PET and T_{mrt} were computed using RAYMAN software (Matzarakis et al. 2007). UTCI was computed based on the program developed by Broede (2009).

Results and discussion

The average PET for the sampled locations varied between 36.8 and 52.4 °C (μPET = 44.57, σ = 3.9). Figure 2 shows the

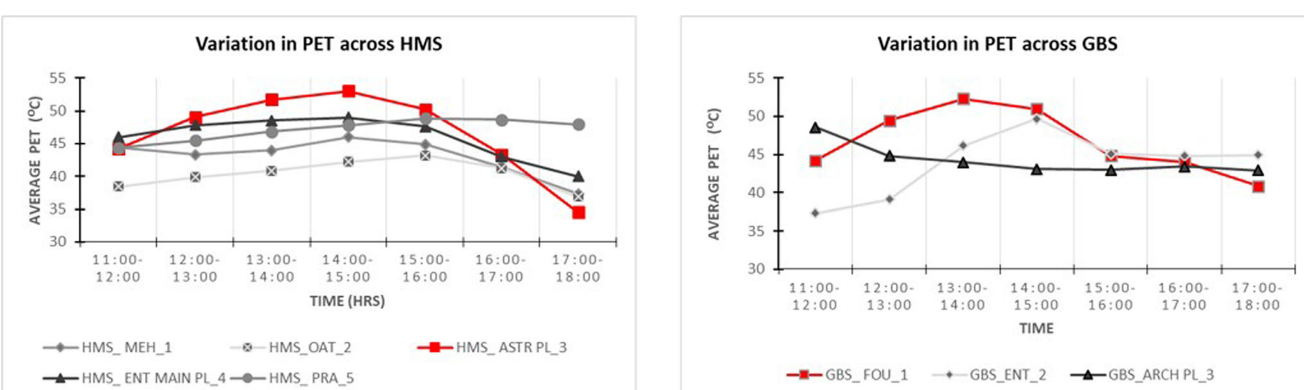


Fig. 2 PET variations across sampled locations in **a** HMS and **b** GBS

hourly variation in average PET in both HMS and GBS from 11:00 to 18:00 h. The sample locations HMS_ASTRPL_3 and GBS_ FOU_1 reported a high PET throughout the day. The values ranged from 34.5 to 53.05 °C ($\mu = 46.5$, $\sigma = 6.45$) and 40.86 to 52.29 °C ($\mu = 46.6$, $\sigma = 4.23$) respectively. The statistical summary of PET across sample locations is presented in Fig. A5 (refer to Supplementary material). Further a strong relationship ($R^2 = 0.83$) was found between PET and sky view factor (SVF) (refer to Supplementary material A6).

A comparison of variation in PET across various sampled locations with the PET scale by Lin et al. (2008) reveal that all the locations corresponded to an extreme physiological stress between 11:00 and 16:00 with an exception of location HMS_OAT_2 (SVF = 0.5) which corresponded to moderate to strong heat stress during 11:00–14:00 h.

The average relative humidity and wind speed in the sampled locations in GBS varied from 23.08 to 40.23% ($\mu = 29.42$, $\sigma = 3.66$) and 0.3 to 0.8 m/s ($\mu = 0.54$, $\sigma = 0.16$) respectively. The average relative humidity and wind speed in the sampled locations in HMS varied from 23.96 to 41.09% ($\mu = 31.7\%$, $\sigma = 4.14$) and 0.0 to 1.42 m/s ($\mu = 0.67$ m/s, $\sigma = 0.4$) respectively.

Locations with a high SVF (0.99) such as GBS_FOU_1 reported large variation in μT_a (38.3 °C) and μT_g (46.2 °C), while location with lower SVF (0.5) HMS_OAT_2 reported lesser variation in μT_a (37.9 °C) and μT_g (40.06 °C) through the day (refer to Supplementary material A7). T_g in GBS_FOU_1 (albedo = 0.24; SVF = 0.99) and HMS_ ENT MAIN PL_4 (albedo = 0.12; SVF = 0.99) varied from 40.67 to 51.6 °C ($\Delta T_g = 10.94$ °C) and 39.24 to 48.04 °C ($\Delta T_g = 8.80$ °C) respectively.

The average T_{mrt} for the sampled locations varied between 41.56 and 52.86 °C ($\mu T_{mrt} = 48.35$, $\sigma = 3.3$). Further, a strong relationship ($R^2 = 0.76$) between T_{mrt} and the sky view factor suggested that locations with a high SVF recorded higher T_{mrt}. T_{mrt} and PET were also strongly correlated ($R^2 = 0.82$) as indicated in A6 (refer to Supplementary material). This indicates that T_{mrt} as an indicator of heat stress is very crucial in outdoor spaces especially in the hot season. PET at the sampled locations was found to be strongly correlated ($R^2 = 0.81$) with SVF. Use of varied surface materials and SVF in the respective sample locations strongly influenced the micrometeorological conditions. The average reflected solar radiation measured between 11:00 and 18:00 h of the exposed red granite surface in HMS (SVF = 0.99) was 65.5 W/m^2 while that of exposed white marble surface in GBS (SVF = 0.99) reported 106.9 W/m^2. Measurements of incident and reflected solar radiation, above each surface, were used to estimate albedo of the surfaces in the squares. The albedo was estimated directly by the ratio of reflected to incident solar radiation considering that the area of the examined surfaces was large enough to avoid any correction regarding the view factor. The albedo value of marble white (+black) used in the GBS was found to be 0.24 and 0.12 for the red granite surfaces used in HMS. These values corresponded well with those reported by Chatzidimitriou et al. (2006).

Subjective assessment

Users perceived the thermal environment as being in the range of warm to hot in both the squares. The subjects predominantly (85.9%) reported warmer thermal sensation (TSV ≥ 2). The mean TSV (μ) registered during the survey was 2.27 ($\sigma = 0.78$). The mean thermal sensation vote (MTSV) was found to be positively correlated ($R^2 = 0.75$) with the SVF of the sampled locations. An increase of 0.5 in SVF value contributed to an increase of nearly 1.5 U in MTSV. The distribution of TSV, HSV, WSV, and SSV are presented in A8 (refer Supplementary material). Majority of the users (78.5%) perceived the sun sensation (SSV) to be in the range of strong to too strong in both the squares. The presence of landscape elements and shading at HMS however resulted in lower percentage of respondents (40%) expressing SSV = 2 as compared to the respondents in GBS (56%). The mean humidity sensation vote in HMS was found to be 0.7 ($\sigma = 0.947$), i.e., it ranged between neutral and sultry. At HMS 67.3% of the respondents expressed (HSV ≥ 1) as compared to GBS (29.1%).

About 62% of the respondents in both the squares found the thermal environment in the squares to be unacceptable while 38% found it to be acceptable. Spearman Roh correlation (refer to T2 in Supplementary material) between the overall thermal sensation (TSV) and HSV, SSV, and WSV revealed that the sun sensation vote (SSV) has a significant correlation (at 0.01 level) with the thermal sensation vote (TSV).

Neutral temperature

The PET values were grouped into data bins of 1 °C intervals and were compared with the mean thermal sensation votes obtained from the subjective survey. The slope of the fitting line signifies the respondents' degree of thermal sensitivity towards PET variation. This was done for both the squares individually and thereafter for the combined dataset. The neutral PET value for HMS was found to be 26.4 °C. The thermal sensation level increased a grade for every 3.24 °C increase in PET values ($R^2 = 0.7$) in HMS as presented in Fig. 3.

The neutral PET value for GBS was found to be 22.1 °C. The thermal sensation level increased a grade for every 2.3 °C increase in PET values ($R = 0.7$). Neutral PET value computed after combining the datasets of both the squares was found to be 24.7 °C ($R^2 = 0.6$). Further, the thermal sensation level increased a grade for every 2.8 °C increase in PET values. Middel et al. (2016) reported that neutral temperature in outdoor spaces found in temperate climates tends to be lower than

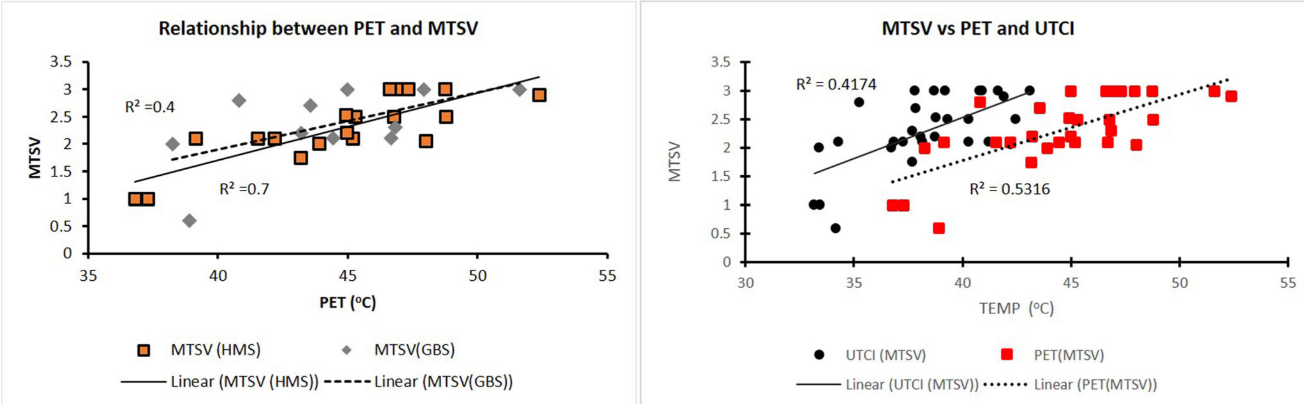


Fig. 3 Relationship between **a** MTSV and PET and **b** MTSV with PET and UTCI

20 °C (e.g., 13.3 °C in Sheffield, UK; 18.5 °C in Kassel, Germany). It usually exceeds 22 °C in subtropical and tropical climates (e.g., 24.0 °C for subtropical Sydney, Australia (Spagnolo and de Dear 2003), 25.6 °C for Taiwan (Lin et al. 2009), 24.41 °C for Guangzhou (Li et al. 2017)). The neutral temperature found in this study (24.74 °C) corresponds well with other studies conducted in the subtropical and tropical climates. The values of the neutral PET range prescribed as per the PET scale (Lin et al. 2008) are 26–30 °C. However, the neutral PET reported in this study is 1.2 °C lower than the lower limit of the PET scale. This can be attributed to adaptation and expectations (Nikolopoulou and Lykoudis 2006) and choice of the religious setting. The relationship between mean thermal sensation votes and PET for all the sampling locations in the studied squares (in summer season) showed a tendency of increased thermal stress with increasing PET. Cohen et al. (2013), Kántor et al. (2012), Lin (2009), Lin et al. (2011), Ng and Cheng (2012), and Yahia and Johansson (2013) have reported similar relationships. A positive correlation was also found between the thermal sensation vote (TSV) and UTCI as shown in Fig. 3b. The neutral UTCI value of 22.9 °C (R^2 = 0.42) computed from data from both the squares corresponds to "no thermal stress" band (+ 9 to + 26 °C) of UTCI scale. A unit change in MTSV corresponds to about 6.9 °C increase in UTCI. In terms of correlation with subjective assessment, PET can be considered as better index for estimating thermal stress in outdoor spaces.

Studies in temperate climates indicate that the number of people visiting an urban public space tends to increase with increase in air temperatures and solar radiation across all seasons (Nikolopoulou et al. 2004). However, studies conducted in hot humid regions show decrease in number of people as the solar radiation increases (Lin 2009). This study investigated the relationship between the presence of sun ($t_g - t_a$) and the hourly attendance in the space. The relation between the attendance in space and μ ($t_g - t_a$) is presented in A9 (refer to Supplementary material). Most of the sampled locations in HMS and GBS exhibited decline in attendance with increase in ($t_g - t_a$) ($R^2 = 0.98$ GBS; $R^2 = 0.72$ HMS) except HMS_ PRA_5. HMS_ PRA_5 continued to be thronged by people seeking Prasad and feeding beggars despite increase in $t_g - t_a$ ($R^2 = 0.74$). This is in contrast to the result reported by Lin et al. (2013), wherein the attendance declined exponentially as ($t_g - t_a$) increased. The exception thus highlighted can be attributed to the uniqueness of a religious square and the associated activity.

Logit was used to analyze the variation in thermal acceptability and preference of respondents compared to variations in PET. Figure 4a presents the relation between PET and thermal acceptability. Figure 4b presents the relation between PET and thermal preference. PET strongly influenced both thermal acceptability and preferences. At the level of 80%, acceptability respondents accept PET value of 39.4 °C. The percentage of people reporting "want no change" reduces with the increase in PET while percentage of people reporting "want cooler" increases with increase in PET. However, respondents desire no change in thermal conditions up to a PET of 34.7 °C. This corresponds to a moderate heat stress as per the PET scale. At a PET of 42 °C which corresponds to the upper limit of "hot thermal conditions" associated with "strong heat stress" on the PET scale (Lin 2009), nearly 44% respondents desire cooler conditions. Eighty percent of the respondents desire cooler conditions at a PET of 47.8 °C.

The influence of temporal, personal, and design variables on TSV is presented as Supplementary material T3. The following subsection elaborates the key determinants that influence thermal perception in HMS and GBS.

Influence of intent of visit

The intended purpose of visit had a significant influence on the thermal perception of the respondents. The relationship between the level of acceptability and PET for people who had visited the squares for primarily worship purposes (49.5%

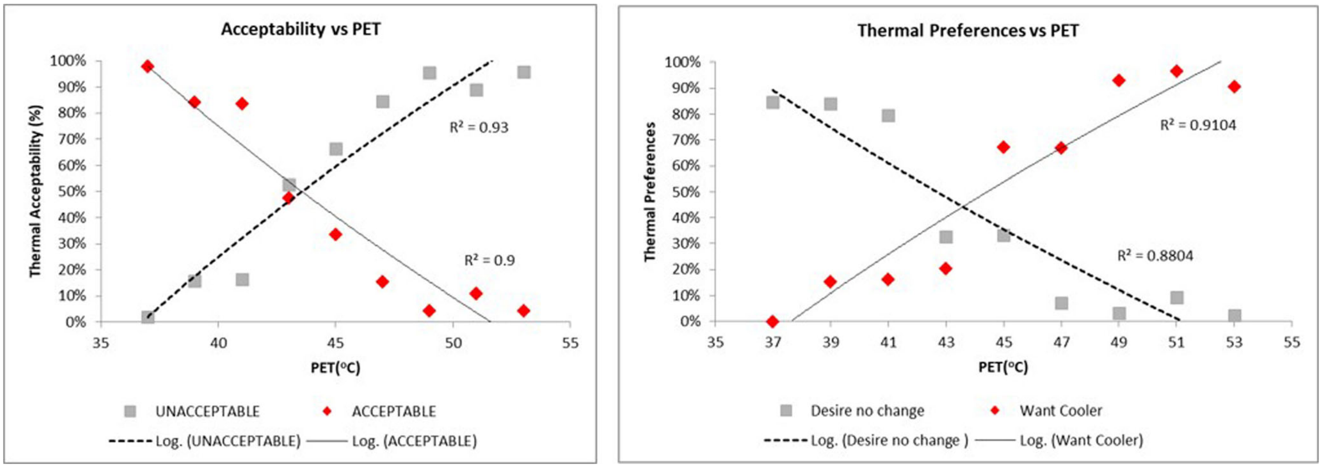


Fig. 4 Relation between PET and **a** thermal acceptability and **b** thermal preference

of the sample) and those for non-worship purposes such as meeting people, passing by, and shopping (59.5% of the sample) is presented in A10 (refer to Supplementary material). The mean TSV for respondents visiting for worship purpose was found to be 2.4 ($\sigma = 0.76$) as compared to 2.18 ($\sigma = 0.77$) for non-worship purposes. The neutral PET value of respondents visiting for non-worship purposes was found to be 2.7 °C lesser than those visiting for worship purposes. This highlights the distinctiveness of the religious setting in itself. However, as the PET increases, those who visited the square for non-worship purposes such as shopping and other activities are more tolerant as compared to the ones visiting for worship purpose. An increase of nearly 2.31 °C PET corresponded to a decrease of 10% acceptability in case of respondents frequenting for non-worship purposes as compared to 1.7 °C PET for the others.

This study thus supports the findings reported by Nikolopoulou et al. (2006), wherein it is highlighted that discomfort is more tolerated when people are in a space by choice.

Influence of solar exposure and thermal history

The solar exposure of the respondent (sun or shade) influenced the thermal perception. The mean TSV for respondents in sun was found to be 2.4 ($\sigma = 0.79$) as compared to 2.0 ($\sigma = 0.75$) for those in shade. A comparison between respondents who were in sun (50.8% of the sample) vs. those in shade (49.2% of the sample) is presented in A10 (refer to Supplementary material). As shown in A10, thermal acceptability was found to be lower for respondents in sun compared to those in sun. At a PET of 45 °C, the acceptability was found to be 35% for respondents in sun as compared to 50% for respondents in shade. However, the rate of decline in thermal acceptability for unit increase in PET was higher for the samples collected in shade as compared to those collected in sun. In case of responses registered "in Sun," there is a reduction of 10% acceptability for every 1.9 °C increase in PET values. However, in the case of responses registered "in shade," there is a reduction of 10% acceptability for every 2.8 °C increase in PET values.

Further, the environment where the respondents had been before the interview affected the thermal perception. The mean TSV for respondents who had been in the sun just prior to the interview was found to be 2.4 ($\sigma = 0.80$), 2 ($\sigma = 0.75$) for those who had been outdoors in shade and 1.9 ($\sigma = 0.75$) for respondents who had been in air conditioned environments. This can be explained based on the fact that the skin and body core temperature of the subjects coming from the air-conditioned space was considerably lower than those who were in the outdoors for a longer time. The outdoor subjects may have been closer to physiological discomfort thresholds (Johansson et al., 2016).

Influence of kinetic state

Thermal perception and acceptability vary based on kinetic state of respondents (at rest vs. in motion in last 15 min). The mean TSV of respondents at rest in last 15 min was found to be 2.0 ($\sigma = 0.82$) and 2.4 ($\sigma = 0.73$) for respondents in motion in last half hour. At the level of 80% acceptability, the respondents who had been at rest accepted higher values of PET (39.6 °C) than those who had been in motion (38.3 °C). The same can be explained on the basis of metabolic activity.

Influence of design attributes

Design attributes such as perceived color of materials used, the luminous environment, and amount of green influenced the thermal perception (refer to T3 in supplementary material). The perceived color tone of materials was found to have a significant effect on thermal perception. 64.8% of the respondents in HMS perceived the color tone of materials used in the square as warm while 72.2% of the respondents at GBS perceived the materials to be cold. The mean TSV for respondents who perceived the color of the materials as warm was found to be higher (2.5; $\sigma = 0.65$) as compared to those who perceived the materials to be cold (2.0 ($\sigma = 0.83$). At the level of 80% acceptability, the respondents who perceived the color tone of the surfaces to be cool accepted higher values of PET (39.6 °C) than those who perceived them to be warm (37.8 °C). This corroborates the findings of Tuan (1974) wherein it was indicated that the perception of colors is closely linked to our temperature senses and experience within our geographical and cultural context.

The thermal perception of respondents varied among sampled locations with distinctly different shade attributes. The satisfaction with the amount of green provided in the squares also influenced the TSV. Respondents who expressed satisfaction with the green provided in the squares (12%) reported lesser thermal stress (mean TSV = 2; $\sigma = 0.97$) as compared to 88% respondents who expressed dissatisfaction with the green (mean TSV = "2.48"; $\sigma = 0.74$). These findings are in keeping with Krüger et al. (2017) which suggest that a site's appearance interferes with "felt" thermal judgment. However, the visual appeal of the space was not found to be significantly correlated to TSV. Marginal difference was found between the mean TSV of respondents who considered the space to be visually appealing (TSV = 2.4; $\sigma = 0.68$) and the others who did not (TSV = 2.25; $\sigma = 0.78$).

Influence of personal variables

Marginal difference was observed between the thermal acceptability among males and females. Of the males, 67.3% found the thermal environment in the square to be unacceptable as compared to 60.8% of the female respondents. Gender seemed to have a statistically significant but weak influence on the thermal perception. Female subjects exhibited higher thermal acceptability and reported lesser thermal stress (31% females reported TSV ≥ 2 as compared to 56% males reporting TSV ≥ "2"). At the level of 80% acceptability, females accepted higher PET (39.2 °C) as compared to males (38.8 °C). Although research by Indraganti et al. (2015) has established that women are more tolerant of the thermal conditions in naturally ventilated office buildings in Hyderabad and Chennai, more studies will be required to verify the same in the case of outdoor thermal comfort in the Indian context.

Age of the subject had a statistically significant but weak influence on the thermal perception. Marginal difference was found between the mean TSV of respondents below the age of 40 years (MTSV = 2.2; $\sigma = 0.80$) and respondents over the age of 40 years (MTSV = 2.42; $\sigma = 0.68$). At the level of 80% acceptability, respondents in the age group of 20–40 years accepted higher PET (39.5 °C) as compared to the respondents above 40 years (38.5 °C).

Evidence of thermal adaptation

HMS was characterized by greater number of trees, better seating opportunitites, and presence of beverage kiosks. Addittionally, rampant use of wet mats and shade by overhead canopies was seen in HMS (refer to Supplementary material for A11, A11.1, and A12). Consequently, people were seen seeking shade under trees or under canopies in HMS. A comparison between the acceptability votes in both the squares revealed that the tolerance of people in GBS was lower as compared to HMS. This is evident from the fact that only 18.5% of the respondents found the thermal environment in GBS to be acceptable as compared to 35% in HMS. This can be attributed to the absence of landscape elements, limited opportunity to seek shade, and perceived control in GBS as compared to HMS.

Ranking of measures to improve thermal acceptability

The respondents were asked to rank their preference among 12 different strategies commonly adopted in response to the thermal stimuli. The list of 12 strategies was obtained through a keyword identification from the pilot survey supported by literature review. Users were asked to rank the most to least preferred choices as well as those which they considered equally preferable. Based on the ranking method proposed by Reffat et al. (2001), the relative importance of the choices were obtained from user responses through the following procedure. The user preferences were transformed to matrices and the relative importance were compared to each other. From these matrices, the individual row scores were calculated for all the users. Assigned weight is calculated by converting the highest row score to 10 in a 10-point scale, and the rest of the row scores are accordingly converted using the same ratio. As shown in Table 3, the overall weight was calculated for each choice and the mean is reported in column (3) of the table by considering all the users. The values would have varied from a maximum of "10" to "0" with respect to various users. From the mean values obtained in column (3) of the table, the relative weight of each choice is evaluated as shown in Table 3.

Provision of drinking water ($\Delta = 1.53$) and seating spaces ($\Delta = 1.29$) which play a key role in thermal adaptation were ranked higher. Further respondents desired shading by tree ($\Delta = 1.4$), followed by shading by canopies ($\Delta = 1.06$) to improve thermal comfort conditions in the outdoor space. A higher ranking obtained for choices such as addition of soft landscape elements such as lawn, water bodies, and flowering species of trees indicates the strong influence of psychological factors and highlight the role of design and landscape elements in influencing thermal perception.

Table 3 Ranking of measures to improve thermal acceptability

S. no.	Choice of measures	Mean of preferences (μ)	Weighted average $\Delta = \mu/\mu_{total} \times 10$
1	Addition of water body	3.61	0.88
2	Addition of lawn	2.90	0.71
3	Addition of flowering plants	5.56	1.36
4	Addition of shrubs	1.61	0.39
5	Shading by canopies	4.33	1.06
6	Shading by tree	5.80	1.42
7	Change of color of surface	2.81	0.69
8	Change in surface finish	1.51	0.37
9	Addition of hard surfaces	0.10	0.03
10	Reduction of hard surfaces	1.08	0.26
11	Seating	5.25	1.29
12	Provision of drinking water	6.25	1.53
	Total (μ_{total})	40.83	10

Conclusion

This study examined the physical and perceived micrometeorological conditions of outdoor spaces associated with religious precincts in HMS and GBS during typical summer days in New Delhi, India. The average PET for the sampled locations varied between 36.8 and 52.4 °C (μPET = 44.57 °C, σ = 3.9). SVF strongly influenced the physical thermal characteristics, PET, and T_{mrt} of the sampled locations. The neutral PET value was found to be 24.7 °C. The neutral PET value of respondents visiting the squares for non-worship purposes was found to be 2.7 °C lesser than those visiting for worship purposes. People visiting the squares for non-worship purpose however were found to be more tolerant of higher PET conditions as compared to others. Worship additionally, the study found that solar exposure, kinetic state, thermal history, and landscape elements influenced the thermal perception. At a PET of 45 °C, the acceptability was found to be 35% for respondents in sun as compared to 50% for respondents in shade. However, the rate of decline in thermal acceptability for unit increase in PET was higher for the the samples collected in shade as compared to those collected in sun. In case of responses registered in Sun, there is a reduction of 10% acceptability for every 1.9 °C increase in PET values. However in the case of responses registered in shade, there is a reduction of 10% acceptability for every 2.8 °C increase in PET values. Marginal difference was observed between the thermal acceptability among males and females. A weighted ranking of preferred choices to improve thermal comfort conditions indicated that respondents desired presence of drinking water followed by provision of shade by trees. A higher ranking obtained for introduction of landscape elements in the space suggests that people perceive landscape elements as being significant in modifying the comfort conditions in outdoor spaces.

Scope for future work

This study should be viewed as an attempt to determine the neutral value of PET in the summer season in New Delhi, India, especially with reference to religious precincts. Work of similar nature can be undertaken to bring forth the thermal characteristics and associated thermal comfort conditions in varied types of outdoor spaces with varying landscape attributes in the Indian context.

Acknowledgements The authors wish to acknowledge the support of administrative authorities for conducting the field studies. Further, the authors are extremely grateful to the reviewers whose valuable and insightful comments helped shape this paper.

References

Ahmed KS (2003) Comfort in urban spaces: defining the boundaries of outdoor thermal comfort for the tropical urban environments. Energ Build 35(1):103–110

Ali SB, Patnaik S (2017) Thermal comfort in urban open spaces: objective assessment and subjective perception study in tropical city of Bhopal, India. Urban Clim 0–1 . doi: https://doi.org/10.1016/j.uclim.2017.11.006

Aljawabra F, Nikolopoulou M (2010) Influence of hot arid climate on the use of outdoor urban spaces and thermal comfort: do cultural and social backgrounds matter? Intell Build Int 2:3, 198–217

ASHRAE (2004) ASHRAE Standard, ANSI/ASHRAE Standard 55-2004: thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta

ASHRAE, ASHRAE/ANSI Standard 55-2010 (2010) Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating, and Air-Conditioning Engineers: Atlanta, GA

ASHRAE (2013) ANSI/ASHRAE Standard 55. Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta

Auliciems A (1981) Towards a psycho-physiological model of thermal perception. Int J Biometeorol 25(2):109–122

Broede P (2009) Program for calculating UTCI Temperature (UTCI). u. V. a. 0.002

Chatzidimitriou A, Chrissomallidou N, Yannas S, Sites U (2006) Ground surface materials and microclimates in urban open spaces. 23rd Conf Passiv Low Energy Archit 485–490

Cohen P, Potchter O, Matzarakis A (2013) Human thermal perception of coastal Mediterranean outdoor urban environments. Appl Geogr 37: 1–10

Fanger PO (1972) Thermal comfort. McGraw Hill, New York

Gagge AP, Fobelets A, Berglund LG (1986) A standard predictive index of human response to the thermal environment. ASHRAE Trans 92: 709–731

Herzog TR (1992) A cognitive analysis of preference for urban spaces. J Environ Psychol 12(3):237–248

Herzog TR, Kaplan S, Kaplan R (1976) The prediction of preference for familiar urban places. Environ Behav 8:627–645

Höppe P (2002) Different aspects of assessing indoor and outdoor thermal comfort. Energy and Buildings 34:661–665

Houghten FC, Yaglou C (1923) Determining lines of equal comfort. ASHVE Trans 29(10):163–176

Humphreys M (1970) A simple theoretical derivation of thermal comfort conditions. J Inst Heat Ven Eng 38:95–98

Indraganti M (2010) Adaptive use of natural ventilation for thermal comfort in Indian apartments. Build Environ 45:1490–1507. https://doi.org/10.1016/j.buildenv.2009.12.013

Indraganti M, Ooka R, Rijal HB (2015) Thermal comfort in offices in India: Behavioral adaptation and the effect of age and gender. Energy and Buildings 103:284–295

Indraganti M, Lee J, Zhang H, Arens E (2016) Why is the Indian Sari an all-weather gear? Clothing insulation of Sari, Salwar-Kurti, Pancha, Lungi, and Dhoti. UC Berkeley: Center for the Built Environment. Retrieved from https://escholarship.org/uc/item/0080t60q

ISO 8996 (2004) Ergonomics of the thermal environment—Determination of metabolic rate. International Organization for Standardization, Geneva

ISO 7730 (2005) 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 Standards Organization, Geneva

Johansson E, Yahia MW, Arroyo I et al (2018) Outdoor thermal comfort in public space in warm-humid Guayaquil, Ecuador. Int J Biometeorol 62:387

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

Klemm W, Heusinkveld BG, Lenzholzer S, Jacobs MM, Van Hove B (2015) Psychological and physical impact of urban green spaces on outdoor thermal comfort during summertime in The Netherlands. Build Environ 83:120–128

Knez I, Thorsson S (2006) Influences of culture and environmental attitude on thermal, emotional and perceptual evaluations of a public square. Int J Biometeorol 50(5):258–268

Knez I, Thorsson S, Eliasson I, Lindberg F (2009) Psychological mechanisms in outdoor place and weather assessment: towards a conceptual model. Int J Biometeorol 53(1):101–111

Krüger E, Drach P, Broede P (2017) Outdoor comfort study in Rio de Janeiro: site-related context effects on reported thermal sensation. Int J Biometeorol 61:463–475

Lenzholzer S (2010) Engrained experience—a comparison of microclimate perception schemata and microclimate measurements in Dutch urban squares. Int J Biometeorol 54:141

Li L, Zhou XQ, Yang L (2017) The Analysis of Outdoor Thermal Comfort in Guangzhou during Summer. Procedia Eng 205:1996–2002

Lin TP (2009) Thermal perception, adaptation and attendance in a public square in hot and humid regions. Build Environ 44:2017–2026

Lin TP, de Dear R, Hwang RL (2011) Effect of thermal adaptation on seasonal outdoor thermal comfort. Int J Climatol 31:302–312

Lin TP, Matzarakis A (2008) Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. Int J Biometeorol 52:281–290

Lin TP, Tsai K-T, Liao C-C, Huang Y-C (2013) Effects of thermal comfort and adaptation on park attendance regarding different shading levels and activity types. Build Environ 59:599–611. https://doi.org/10.1016/j.buildenv.2012.10.005

Lindal PJ, Hartig T (2013) Architectural variation, building height, and the restorative quality of urban residential streetscapes. J Environ Psychol 33:26–36

Matzarakis A, Rutz F, Mayer H (2007) Int J Biometeorol 51:323. https://doi.org/10.1007/s00484-006-0061-8

Mayer H, Höppe P (1987) Thermal comfort of man in different urban environments. Theor Appl Climatol 38(1):43–49

Middel A, Selover N, Hagen B, Chhetri N (2016) Impact of shade on outdoor thermal comfort—a seasonal field study in Tempe, Arizona. Int J Biometeorol 60:1849. https://doi.org/10.1007/s00484-016-1172-5

Monteiro LM, Alucci MP (2012) Thermal comfort in central areas of Sao Paulo, Brazil. In: Bodart M, Evrard A (eds) , vol I. Architecture & sustainable development, Presses universitaires de Louvain, Lovain-la-Neuve, pp 433–438

Nikolopoulou M (2011) Outdoor thermal comfort. Front Biosci 3:1552–1568

Nikolopoulou M, Lykoudis S (2006) Thermal comfort in outdoor urban spaces: analysis across different European countries. Build Environ 41(11):1455–1470

Nikolopoulou M, (coord.), Kofoed N, Gaardsted M, Scudo G, Dessi V, Rogora A, Steemers K, Ramos M, Sinou M, Katzschner L, Bosch U, Roettgen M, Compagnon R, Goyette-Pernot J, Kang J, Yang W, Zhang M, Chrisomallidou N, Chrisomallidis M, Theodosiou T, Avdelidi K (2004) RUROS: rediscovering the urban realm and open spaces. CRES edition, Athens. http://alpha.cres.gr/ruros/ (Accessed 7 Sept 2017)

Ng E, Cheng V (2012) Urban human thermal comfort in hot and humid Hong Kong. Energy Buildings 55:51–65

Reffat RM, Harkness EL (2001) Environmental Comfort Criteria: Weighting and Integration. J Perform Constr Facil 15(3):104–108

Rohles FH (1980) Temperature or temperament—a psychologist looks at thermal comfort. ASHRAE Trans:541–551

Siple P, Passel C (1945) Measurements of dry atmospheric cooling in subfreezing temperatures. Proc Am Philos Soc 89(1):177–199

Smardon RC (1988) Perception and aesthetics of the urban environment review of the role of vegetation. Landsc Urban Plan 15(1–2):85–106

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

Thom EC (1959) The discomfort index. Weatherwise 12:2, 57–61. https://doi.org/10.1080/00431672.1959.9926960

Tseliou A, Tsiros IX, Lykoudis S, Nikolopoulou M (2010) An evaluation of three biometeorological indices for human thermal comfort in urban outdoor areas under real climatic conditions. Build Environ 45:1346–1352. https://doi.org/10.1016/j.buildenv.2009.11.009

Tuan Y-F (1974) Topophilia: A study of environmental perception, attitudes, and values. Prentice-Hall, Englewood Cliffs

Vasilikou (2015) The Role of Urban Morphology and Pedestrian Movement in the Perception of Thermal Comfort in Historic City Centres, PhD thesis Architecture & Planning, University of Kent, Canterbury

Yahia MW, Johansson E (2013) 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(4):615–630

Zacharias J, Stathopoulos T, Wu H (2001) Microclimate and downtown open space activity. Environ Behav 33(2):296–315