Building and Environment 94 (2015) 644–653

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Studies of thermal comfort and space use in an urban park square in cool and cold seasons in Shanghai

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ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form
15 October 2015
Accepted 27 October 2015
Available online 31 October 2015

Keywords:
Outdoor thermal comfort
Urban open space
Thermal sensation vote
PET
Cool and cold seasons
Shanghai

ABSTRACT

Outdoor open space is important to cities and can provide benefits for healthy urban living. Among the many factors that affect space quality and space use, thermal comfort has drawn increasing attention from both climatologists and planners. Previous studies mostly focus on hot seasons when the primary concern is to avoid solar exposure and mitigate heat stress. In Shanghai, because of the high indoor humidity, people prefer to go outdoors and enjoy more sunshine in autumn and winter. This paper presents a thermal comfort survey in one urban park in Shanghai from November to January to investigate the role thermal comfort plays in affecting people's evaluation of the outdoor space and activity. Meteorological measurements, questionnaire surveys and unobtrusive observations were carried out. Computer simulations were conducted to evaluate the micro-meteorological conditions. The physiological equivalent temperature (PET) was used to evaluate people's objective thermal comfort level based on micro-meteorological conditions. It is found that visitors' overall comfort was largely affected by their subjective thermal sensation vote (TSV). In winter TSV showed the strongest positive relationship with air temperature and solar radiation, which are also the two most important factors that affect visitors' space use. The study reveals that the neutral PET in Shanghai in winter is around 15–29 °C. It was also found that duration of stay and length of residence in Shanghai affected visitors' thermal adaptation. This study can provide understandings of people's outdoor thermal comfort in autumn and winter in Shanghai and help promote outdoor space use.

1. Introduction

More than half of the world's population nowadays lives in cities. With more people coming to live and work in cities, urban public open spaces become even scarcer. Urban open spaces, such as squares, green spaces, or parks can provide environmental, ecological, social and economic benefits to cities and are indispensable for healthy urban living [1–3]. To improve the quality of the outdoor environment and attract more people to use the space is the ultimate goal for urban space design [4,5]. The local micro-meteorological condition of the urban space, such as air temperature, wind speed and solar radiation significantly affects visitors' comfort and behavior. The understanding of important micro-meteorological factors as how they affect visitors' evaluation of the space is essential for urban space design and city renewal.

Outdoor thermal comfort study has been an active research field for the past decade [6]. The great majority of the studies are for open spaces [7–12], while there are also a few studies that focus on streets, pathways and routes where pedestrian's thermal comfort conditions were investigated [13–17]. A common agreement has been reached by researchers and practitioners that outdoor thermal comfort is a complex issue, and a pure physiological approach which looks at people's thermoregulation is not enough, as people outdoors are also affected by psychological factors and long term experience, and cultural background, etc. [18–21]. Previous studies in this direction mostly focus on summer when the primary concern is to avoid excessive solar exposure and mitigate heat stress for outdoor activity [10,22–26]. The few studies that look at non heat-dominant micro-meteorological conditions include [27] in Tianjin, a northern China city, and [7] for a city in Taiwan. The

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http://dx.doi.org/10.1016/j.buildenv.2015.10.020
0360-1323/

studies reveal different patterns in terms of people's perception of the thermal environment. For example, the physiological condition considered as “cold” by people in Taiwan is only considered as “neutral” for people in Tianjin [27]. The discrepancy suggests that the findings are quite sensitive to locations, and are related to the climate, convention, culture, and lifestyle of the local residents. For example, Thorsson et al. [24] found that eastern (Japanese) people tend to avoid direct sunshine and seek shade in summer, while in Sweden (Europe) sunbathing is a popular outdoor activity even when the weather is hot. Therefore research findings need to be interpreted in a societal context to be translated to pertinent design implications.

Shanghai is the biggest city in China and has a very unique lifestyle from cities in northern China. For example, in autumn and winter, because of the high indoor humidity, and no pre-fixed radiator by housing regulation, people in Shanghai prefer to go outdoors and enjoy more sunshine when the weather is good. In such a case, it is interesting to investigate the role thermal comfort plays in affecting people's assessment of the outdoor space quality and their activity. The understanding will help to redesign the outdoor space to attract more people.

The objective of this paper is twofold. Firstly, it aims to examine the relationship between outdoor micro-meteorological conditions and people's thermal comfort perception in cool and cold seasons through questionnaire surveys, meteorological measurements and physiological modeling, and identify the most important factors that affect people's evaluation. Secondly, it attempts to relate people's thermal comfort perception with the space use and attendance, and provide understandings of climate-sensitive design that can improve space quality and promote space use. An urban park square in downtown Shanghai is selected as an example in this study.

2. Methods

2.1. Study area

Shanghai (30°40′N ~ 31°53′N, 120°51′E ~ 122°12′E), the biggest city in China, is located on the alluvial terrace of the Yangtze River delta with average elevation of 4 m above sea level. It has a northern subtropical monsoon climate, with a mean annual air temperature of 17.2 °C, and monthly maximum and minimum mean air temperature of 30.2 °C in July and 1.9 °C in January, respectively. The mean annual precipitation averages 902.9 mm, with more than 60% of the rainfall occurring during May and September (2009–2014 data). The city's administrative boundaries cover a total terrestrial area of 6340.5 km^2 excluding estuary waters. The city has a total population of 24.15 million, including both permanent and non-permanent residents [28].

Zhongshan Park is located in the center of the Changning district, which is one of Shanghai's most developed districts. It has a size of 214,200 m^2, with 118,600 m^2 of green space with trees and bushes, 36,900 m^2 of grassland, and 12,200 m^2 of waters. The nearest metro station Zhongshan Park Station is the transit station for Shanghai metro Line 2, 3 and 4. The surrounding neighborhood is a mixture of commercial streets and residential community (Fig. 1, middle). Because of the convenient location and good environment, a lot of people come to visit this park both on weekdays and over the weekends. The park has good facilities for outdoor recreation and exercise. The study site is a square in the center of the park, with the size of approximately 100 m by 100 m. The square is surrounded by trees and benches, and is restricted to pedestrians and baby carriages only. It is next to the main route that traverses the park, and therefore is used by a lot of visitors for resting and recreation. There are residential buildings over 200 m tall to the west of the square outside the park. Fig. 2 shows the typical scenarios in the square.

2.2. Survey campaign

Questionnaire surveys were carried out from November 2014 to January 2015. A total of 5 survey trips were conducted, on November 4th (NOV-04), 14th (NOV-14), December 23rd (DEC-23), January 08th (JAN-08), and 10th (JAN-10). The two surveys in November represent the autumn season, and the three surveys in December and January represent the winter season. The surveys include different weather conditions, such as sunny or cloudy; on the other hand adverse weather conditions such as windy, rainy or snowy days were avoided. The surveys started from 10:00 am to avoid morning peak hours when a lot of people pass the park going to work. The surveys ended at 2:00 to 3:00 pm depending on visitors' attendance.

The questionnaire used was constructed based on ISO 10551:1995 Ergonomics of the thermal environment – Assessment of the influence of the thermal environment using subjective judgment scales, and the Chinese modified version, GBT 18977-2003. It consists of three sections. The first section records respondents' thermal sensation and preference. Demographic information such as age and gender was collected. The traditional ASHRAE 7-point TSV scale was adopted to record the respondents' thermal sensation scale (−3 very cold, −2 cold, −1 a bit cold, 0 neutrality, +1 a bit hot, +2 hot and +3 very hot). Preferences of the four meteorological factors, i.e., air temperature, wind speed, relative humidity and solar radiation were described by a 5-point scale (−2 decrease, −1 little decrease, 0 stay the same, +1 little increase, +2 increase). The second section records respondents' thermal adaptation and deals with the behavioral aspects. Information including their thermal experience, trip purpose, activity type, attitudes towards the urban environment, and social background such as length of residence in Shanghai was surveyed. The third section is completed by the interviewers and records the respondents clothing. Fig. 3 shows the used questionnaire. Meanwhile, the number of individuals in the square was counted by unobtrusive observations together with the use of panoramic pictures at 15 min intervals. Since there were people entering and leaving the square all the time, so the exact attendance number was hard to obtain. Therefore the count was rounded to the nearest 5 or 10. The visitors' activity types were also recorded.

2.3. Micro-meteorological measurement and simulation

In-situ micro-meteorological measurements were conducted for the five surveying days. Two tailor-made mobile micro-meteorological stations were employed, which collected meteorological parameters including air temperature (T_a), globe temperature (T_g), relative humidity (RH), wind speed (V) and global radiation (G). One station was placed at the center of the square (Point A in Fig. 1 Right), and the other was placed under shading (Point B in Fig. 1 Right). Fig. 4 shows the micro-meteorological station. In particular, the globe thermometer consists of a hollow acrylic ping pong ball coated in flat grey paint, with RAL value of 7001 as suggested by Ref. [29]. The diameter of the globe is 40 mm, and a HOBO temperature sensor is mounted at the center. Table 1 shows the specifications of the sensors used to measure the micro-meteorological parameters. The measurement height was 1.2 m, corresponding to the average height of the center of gravity for adults. The sensors had a sampling rate of 10 s. All instruments were calibrated in lab before field survey.

On the other hand, computer simulations were conducted to examine the spatial variation of the micro-meteorological

Fig. 1. Left: Location of Zhongshan Park in Shanghai. Middle: Google Map showing the study site in Zhongshan Park and surrounding neighborhood. The circle indicates Zhongshan Park, and the rectangle indicates the study site. Right: Detailed plan of the study site. A and B indicate the positions of the micro-meteorological stations.

Fig. 2. Pictures of the study site, taken between November 2014 to January 2015.

conditions, such as the mean radiant temperature (T_{mrt}) which is the most important factor that affects thermal comfort. The micro-meteorological modeling software of SOLWEIG [30,31] was used. Building database was acquired, and on-site surveys were carried out to collect information such as tree height, trunk height, and canopy diameter, which was used as input for SOLWEIG simulation.

2.4. Thermal comfort analysis

The human-biometeorological index of PET [32] was employed to evaluate visitors' objective thermal comfort level as directed by the local micro-meteorological conditions. PET is defined as the air temperature in a typical indoor setting at which the human energy budget is maintained by the same skin temperature and sweat rate as those under the conditions to be assessed [33]. PET was selected because it has been widely used in outdoor thermal comfort studies in various climates [24,34–37], and it will provide common protocols for comparison between different studies. The PET value was calculated by a self-developed graphical user interface (GUI) [38] based on the MEMI model [33], with input parameters of T_a, T_{mrt}, RH (based on which the originally input parameter of vapor pressure required by MEMI was calculated), V and human factors. In particular, the most important parameter that determines PET is the T_{mrt}, and it was calculated from the globe temperature T_g with the commonly adapted methods by Ref. [29].

$$T_{mrt} = [(T_g + 273.15)^4 + 1.1 \times 10^8 V^{0.6} / \varepsilon\, D^{0.4} \times (T_g - T_a)]^{1/4} - 273.15 \quad (1)$$

where T_g [°C] is the globe temperature, V [m/s] is the air velocity, T_a [°C] is the air temperature, ε is the emissivity of the sphere (= 0.97 for a flat grey globe used in this study), and D [m] is the diameter of the sphere (= 0.04).

3. Results

3.1. Interview results

A total number of 596 eligible questionnaires were collected, 163 for autumn and 433 for winter. 40.9% of the respondents were male. The most frequent age group was under 30 years old (56.9%), followed by 30–50 years old (28.7%). Most respondents have lived in Shanghai for more than 3 years (63.8%). The primary reason for visiting the park is to rest (42.9%), followed by passing by (24.1%). Most of them had been walking for the past 15 min (40.1%), followed by sitting (27.3%). Most of the respondents had stayed in the park for 15–30 min (40.3%), followed by shorter than 15 min (36.2%). The sample information is summarized in Table 2. Table 3 summarizes the number of people in the square at different time for each survey day. The period between 12:00 to 13:00 was not included, as during this time most visitors left the park to have

Questionnaire for thermal comfort survey

Date：yyyy/mm/dd Time：hh:mm Location：□sun □shade Gender：□M □F

1.Age：□≤29 □30-49 □≥50

2. How do you feel the current environment (single choice)
□very cold □cold □a bit cold □neutral □a bit hot □hot □very hot

3. You feel… (single choice)
□uncomfortable □neutral □comfortable

4. You will be more comfortable if the environment (single choice for each)

temperature：	□colder	□a bit colder	□same	□a bit hotter	□hotter
wind speed：	□lower	□a bit lower	□same	□a bit higher	□higher
humidity：	□drier	□a bit drier	□same	□a bit wetter	□wetter
sunshine：	□weaker	□a bit weaker	□same	□a bit stronger	□stronger

5. Your purpose for this visit is (single choice)
□pass by □meet with friend □rest □exercise

□others(please specify)__________

6. Were you in air-conditioned environment for the past 15 minutes? (single choice)
□Y □N

7. What is your activity for the past 15 minutes? (single choice)
□sports (intense) □sports (medium) □sports(low) □sitting □standing □walking

8. How long have you been here (single choice)
□<15 min □15-30 min □30-60 min □>60 min

9. You choose this place because (multiple choices)
□convenient □quiet □good air □good scene □safe □thermal comfort

□others________

10. Are you a more urban person (enjoying streets, shops, air-conditioning) or a more natural person (enjoying parks, grass and trees)?
□Natural □a bit natural □neutral □a bit urban □urban

11.How long have you been in Shanghai?
□<1 month □1—3 month □3—6 month □0.5—1 year □1—3 years □>3 years

Fig. 3. Thermal comfort questionnaire used in this study.

lunch, resulting in very low attendance count.

3.2. Meteorological conditions

Table 4 gives the statistical summary of the local micro-meteorological conditions at the study site during survey period measured by two micro-meteorological stations. It can be seen that the two days of NOV-04 and NOV-14 represent the climatic feature of typical autumn weather in Shanghai, with mean T_a around 20 °C, and RH less than 50%. On the other hand, the coldest day occurred on JAN-08, with mean T_a around 11.8. All 5 days were calm days, with mean wind speed around 1–2 m/s.

3.3. Micro-meteorological simulation

The computer software of SOLWEIG was calibrated with measurement data. Fig. 5 shows the shadow map at 10:00, 12:00, and 14:00 for each survey day. And Fig. 6 shows the T_{mrt} map at 10:00, 12:00, and 14:00 for each survey day. It could be seen that the local micro-meteorological condition in the square was greatly affected by the buildings over 200 m tall to the west of the square. For all survey days, after 14:00 most of the square was in shadow casted by the buildings, resulting very low T_{mrt} in winter (below 15 °C). In contrast, in the morning there was plenty of sunshine in the square, and local T_{mrt} could be over 40 °C in autumn in sunlit area.

3.4. Thermal sensation vote

Fig. 7 shows the percentage distributions of thermal sensation votes (TSV) in the study site for autumn and winter. Both distributions follow a "distorted" normal distribution pattern, with the left side of the bell (cold side) significantly higher than the right side (hot side). Notably, for the autumn season when the weather was cool, the highest percentage of TSV was "neutral", being 69.9%,

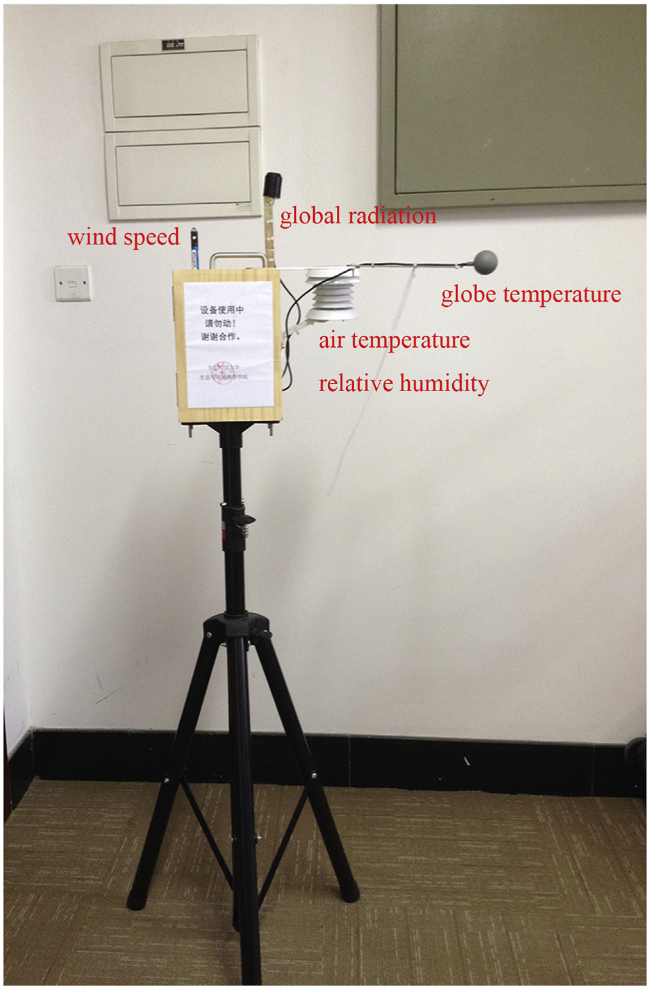

Fig. 4. Micro-meteorological station.

followed by “a bit cold” (19.6%) and “a bit hot” (5.5%). In the winter season, the highest percentage of TSV was also “neutral”, being 53.6%, followed by “a bit cold” (23.3%) and “cold” (14.1%). The results agree with the common knowledge that in cold season people become more accustomed and adapted to coldness, and are consistent with findings in previous studies in cool and cold seasons [27].

Fig. 8 shows the percentage distribution of comfort vote in relation to TSV. The figure illustrates the contribution of thermal comfort perception on visitor's overall evaluation of the square. The distribution shows that, people normally consider coldness as uncomfortable in cool and cold weathers. For example, in autumn 57.1% of the respondents considering the environment as “cold” felt uncomfortable, and only 30.0% of them felt comfortable; on the other hand, 57.8% of the respondents considering the environment as “a bit warm” felt comfortable. The winter case showed a more

Table 2
Summary of the sample used in the study.

Sample size		596	%
Gender	Male	244	40.9
	Female	352	59.1
Age Group	Under 30	339	56.9
	30 to 50	171	28.7
	Above 50	86	14.4
Length of residence in Shanghai	Less than 1 month	42	7.0
	1 to 3 months	16	2.7
	3 to 6 months	32	5.4
	0.5–1 year	34	5.7
	1 to 3 years	92	15.4
	3 years above	380	63.8

Table 3
Attendance count at the square at different time for each survey day. The “–” mark indicates no data because of the termination of the survey.

	10:00	10:30	11:00	11:30	13:00	13:30	14:00	14:30
NOV-04	40	50	60	45	55	40	60	40
NOV-14	75	80	55	50	55	25	–	–
DEC-23	40	60	55	30	25	–	–	–
JAN-08	25	50	25	20	30	25	–	–
JAN-10	40	50	60	45	55	40	60	80

significant trend: 66.7% of the respondents considering the environment as “very cold” felt uncomfortable, whereas no respondents felt comfortable when they felt “very cold”; in contrast 73.3% of the respondents considering the environment as “a bit hot” felt comfortable, followed by 50.2% of the respondents who considered the environment as “a bit cold” and felt comfortable. In autumn, the rates of respondents voting for uncomfortable, neutral and comfortable were 13.4%, 36.1% and 51.5%, respectively; whereas in winter the rates were 23.6%, 45.1% and 31.3%, respectively.

4. Analysis and discussions

4.1. Subjective VS. Objective estimation

The visitors' subjective thermal sensations were characterized by TSV, and the objective estimation of their thermal comfort level were calculated by the human-biometeorological index of PET as determined by the local micro-meteorological factors (T_a, T_{mrt}, V and RH). To compare between subjective and objective estimations, Pearson correlation analyses were carried out between TSV and the micro-meteorological factors and also PET. The results showed that, in autumn TSV had the strongest correlation with RH, with Pearson correlation coefficient $r = 0.18$ ($P < 0.01$), followed by V with $r = -0.11$; in winter, the strongest correlation was with T_a with $r = 0.29$, followed by PET with $r = 0.20$, and T_{mrt} with $r = 0.13$, the correlation with V was also negative, with $r = -0.08$;

To further examine the relationship between PET and visitors' subjective thermal sensations and get the neutral PET, the mean thermal sensation votes (MTSVs) were calculated as suggested by Ref. [7]. The PET range for autumn season was 13 °C–30 °C, while

Table 1
Meteorological sensors used for micro-meteorological measurement.

Parameter	Sensor	Range	Accuracy
Air temperature (T_a)	HOBO S-THB-M002	−40 °C–75 °C	±0.2 K from 0° to 50 °C
Globe temperature (T_g)	HOBO S-TMB-M002	−40 °C–100 °C	±0.2 K from 0° to 50 °C
Relative humidity (RH)	HOBO S-THB-M002	0–100%	±2.5%
Wind speed (V)	AccuSense T-DCI-F900-S-P	0.15–10 m/s	±0.05 m/s
Global radiation (G)	HOBO S-LIB-M003	0–1280 W/m^2	±10 W/m^2 or ±5%

Table 4
Summary of meteorological measurement result.

Date	T_a (°C)			T_g (°C)			G (W/m^2)			RH (%)			V (m/s)		
	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
NOV-04	21.1	17.8	19.4	28.8	20.4	25.7	665.6	79.4	472.9	45.6	34.9	40.8	3.2	0.05	0.98
NOV-14	18.9	15.2	17.0	26.1	18.0	22.3	646.9	90.6	494.5	36.3	26.6	30.3	2.3	0.08	1.10
DEC-23	13.5	10.3	12.1	19.6	13.1	16.8	580.6	63.1	471.0	50.9	42	47.3	2.7	0.05	1.86
JAN-08	9.2	5.4	7.7	15.0	8.7	11.8	571.9	78.1	432.2	41.6	28.8	34.6	3.9	0.15	2.13
JAN-10	14.4	9.6	12.6	19.8	11.5	16.0	526.9	56.9	300.9	51.9	32.1	41.9	3.0	0.06	1.26

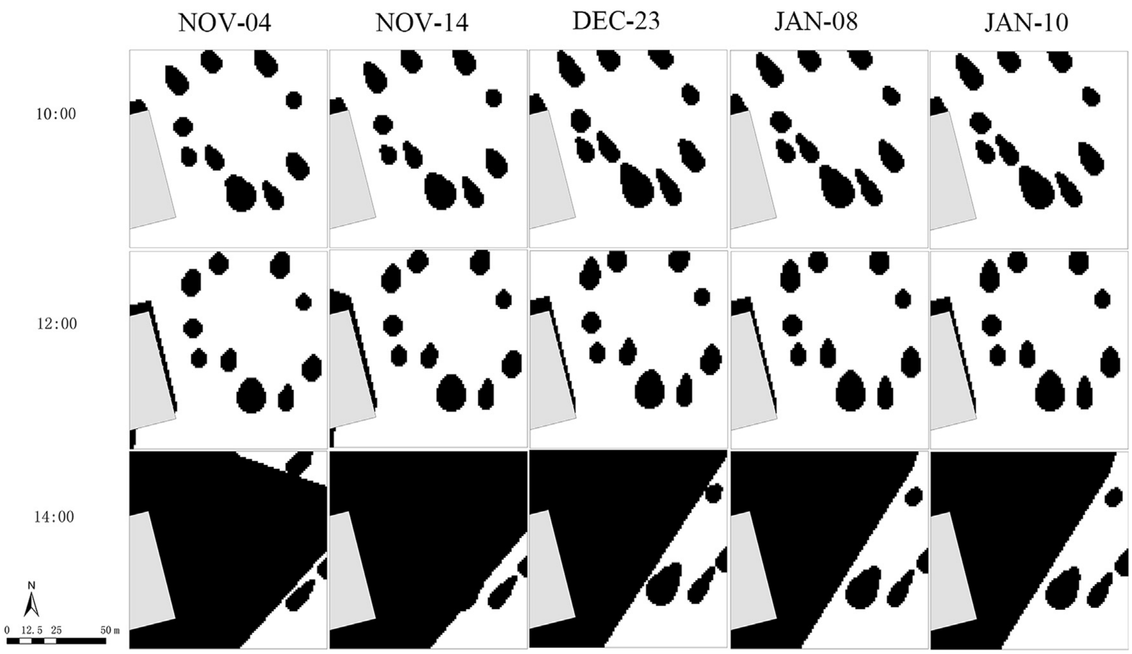

Fig. 5. Shadow map at 10:00, 12:00, and 14:00 for each survey day.

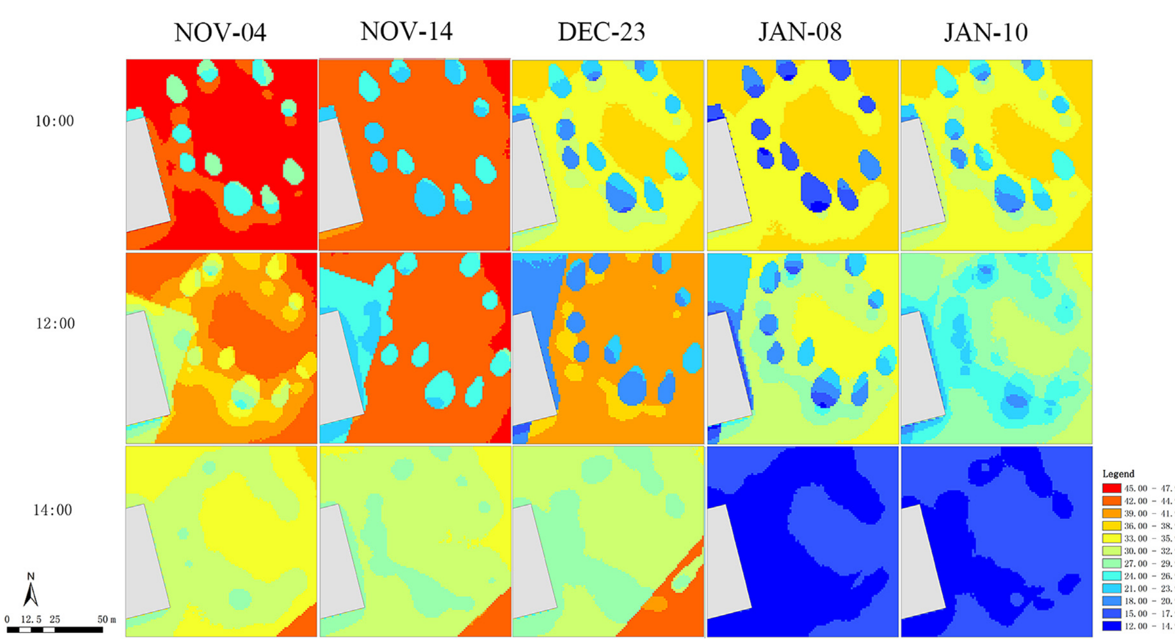

Fig. 6. T_{mrt} map at 10:00, 12:00, and 14:00 for each survey day.

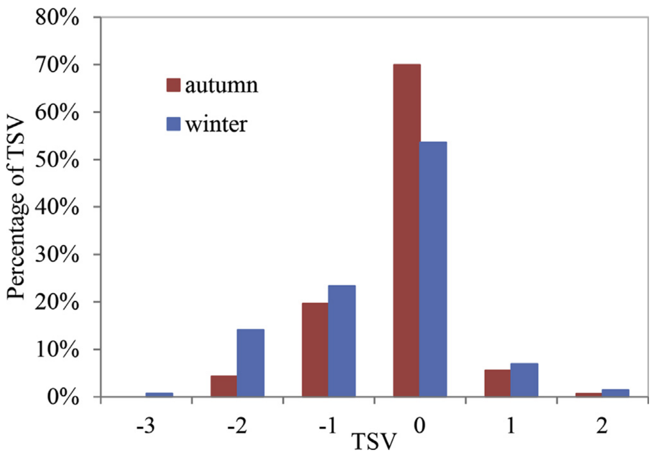

Fig. 7. Percentage distributions of thermal sensation votes (TSV) in the square.

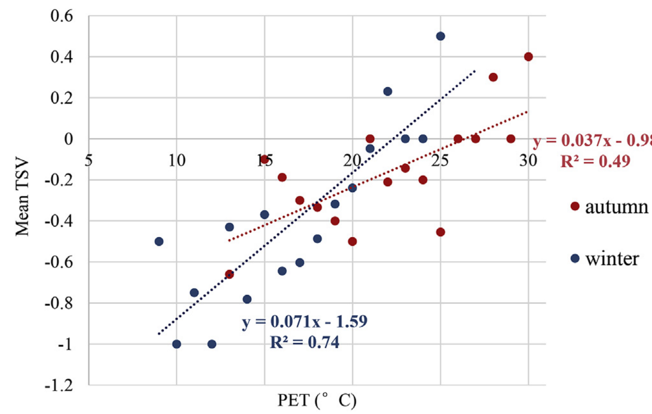

Fig. 9. Correlation between the mean thermal sensation votes (MTSVs) and PET in autumn and winter seasons.

for winter season was 9 °C–25 °C. For each 1 K of PET range, the MTSV was calculated. Linear regression was conducted between MTSV and PET to get the neutral PET. Fig. 9 shows the correlation between MTSV and PET. The regression functions are given as follows:

For autumn: $MTSV = 0.037 \times PET - 0.98\ (R^2 = 0.49)$ (2)

For winter: $MTSV = 0.071 \times PET - 1.59\ (R^2 = 0.74)$ (3)

The lower correlation coefficient (R^2) for autumn season could be explained by the moderate weather, i.e., respondents generally didn't have strong sensations towards the micro-meteorological conditions, therefore most of their TSVs were “neutral” despite different PETs, which caused a lot of MTSVs occurring around 0. In particular, the regression coefficient is only 0.037, meaning that a broad range of 27 K of PET would correspond to the same TSV class. This is hardly the case in reality, but reflects that the respondents were insensitive to the moderate and cool weather. In contrast, in winter the respondents were more sensitive to micro-meteorological factors such as T_a V, and G. Accordingly the correlation was much better, with $R^2 = 0.74$ and also higher regression coefficient of 0.071. Through regression using winter data, the neutral PET range for Shanghai was 15–29 °C, which is comparable to the range of Tianjin (11–24 °C) [27], and much wider than that of Europe (26–30 °C) [39] and Taiwan (18–23 °C) [40]. The wide acceptability of thermal comfort sensation could be attributed to the various meteorological conditions in Shanghai even for the same season. For example, for the 3 survey days between late December and early January, which is commonly considered as the coldest time of year in Shanghai, the measured T_a during survey period varied between 9 and 20 °C, and RH varied between 30 and 50%. People living in Shanghai get adapted to such diverse weather conditions, therefore have wider thermal sensation range compared to residents living in high-latitude or low-latitude regions.

4.2. Preference of micro-meteorological condition

Fig. 10 shows respondents' preference of local micro-meteorological parameters, including T_a, RH, V, and G. The results revealed that the majority of respondents preferred “same” weather conditions: 51.5% for T_a, 39.2% for RH, 56.4% for V and 57.1% for G in autumn, and 40.2% for T_a, 36.5% for RH, 45.5% for V, and 48.3% for G in winter. This was consistent with the fact that most respondents' overall comfort votes were “comfortable” or “neutral”, indicating visitors were generally satisfied with the local environment including thermal condition. Another noticeable feature is respondents' strong preference to higher RH, accounting for 52.1% for autumn and 56.3% for winter including both “increase” and

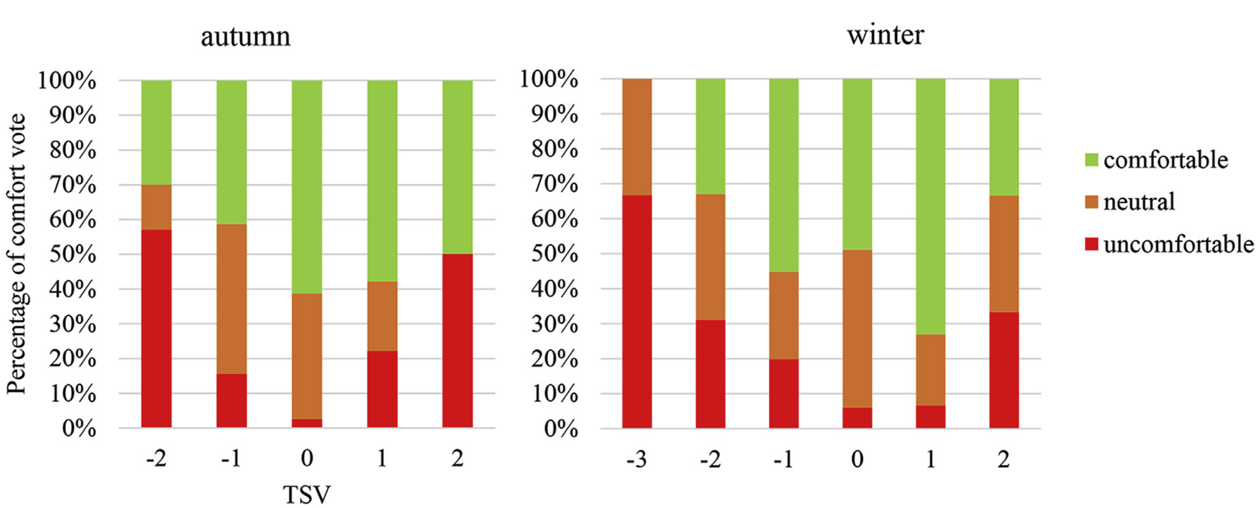

Fig. 8. Percentage distributions of comfort vote in relation to TSV in the square.

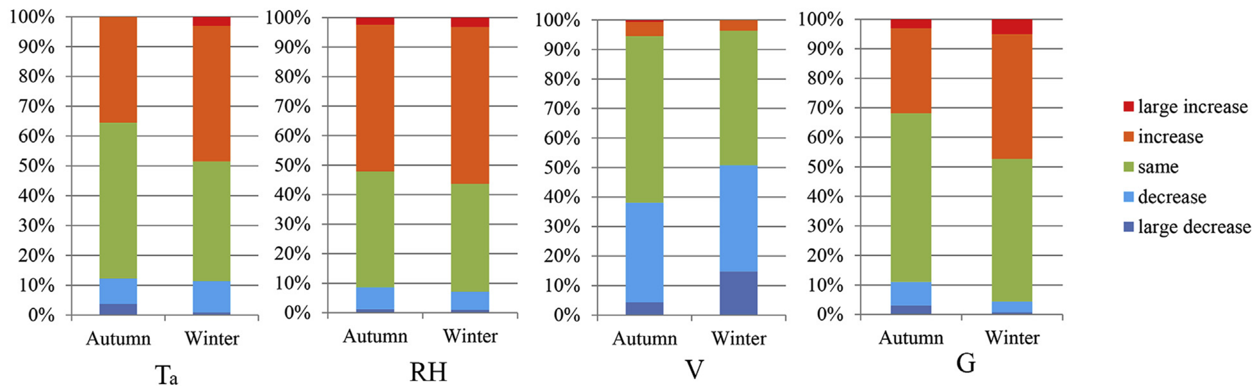

Fig. 10. Preference votes for micro-meteorological parameters of T_a, RH, V, and G in autumn and winter.

"large increase". Shanghai has a humid climate, with daytime RH normally around 90% in summer. People living in Shanghai are constantly exposed to high RH, therefore in winter when the RH is below 40% people already feel uncomfortable. Furthermore, respondents also preferred higher T_a (35.6% and 48.5% for autumn and winter, respectively) and G (31.9% and 47.3% for autumn and winter, respectively), but lower V (38.0% and 40.8% for autumn and winter, respectively).

4.3. Adaptation to thermal comfort: short-term and long-term adaptations

In order to examine how the respondents' adaptation had affected their thermal sensations, several behavior-related factors which were considered to be important for thermal adaptation were surveyed, including both short-term experience, such as purpose of visit (PP), activity for the past 15 min (ACT), duration of stay (DR), and whether in air-conditioning rooms for the past 15 min (AC), and long-term experience such as length of residence in Shanghai (YEAR). These factors were labeled and compared against respondents' TSVs. Because these factors were non-parametric, and the respondents' votes might not necessarily follow normal distributions, therefore the Kruskal Wallis H Test was used to examine if the TSVs were affected by the adaptation factors, which was also the test method used in Ref. [23]. The TSVs were grouped by different labels, and p values for the null hypothesis ("Different groups don't have significant differences for TSVs.") were calculated. For the autumn case, the p values for PP, ACT, DR, AC and YEAR were 0.107, 0.308, 0.164, 0.502 and 0.329, respectively. These values were all larger than the 0.05 threshold, suggesting that there were no significant relationships between TSV and these adaptation factors. In the winter case, the p values for PP, ACT, and AC were 0.505, 0.335, and 0.509, respectively, again indicating respondents' TSVs were not necessarily affected by these factors. The irrelevance of recent air-conditioning experience in affecting TSV was different from results found in heat-dominant environment such as Singapore [23]. The reason for the difference may be because in winter, air-conditioning in Shanghai is normally for heating, and people coming out of warm rooms to have exposure to sunshine may not be as sensitive as people from cool rooms to hot environment.

Notably, the p value for DR and YEAR for winter were 2.89e-5 and 0.075, respectively. The low value for DR (<0.01) suggested that there were significant differences between different groups, i.e., time of stay in the site. Fig. 11 shows the percentage distributions of TSVs for different groups. It can be seen from the figure that shorter time of stays normally leaded to lower TSVs, such as −2 and −1, and longer time of stays normally leaded to neutral TSV. One possible interpretation of this result is that visitors already feeling comfortable with the environment tended to stay longer. However, after checking the overall comfort vote distribution (also refer to Fig. 8) for the 4 DR groups, the percentage of comfort votes including "comfortable" and "neutral" was not found to have a positive correlation with DR. In fact no substantial differences were found among different groups: comfort votes accounted for 89.4%–95.2% for different groups for autumn, and 85.3%–91.2% for winter. As the visitors were reported to generally have a high level of overall comfort, the influence of comfort on their duration of stay at the square could not be revealed in this study. This limitation needs to be considered in future work. More diverse study sites with various micro-meteorological conditions should be added therefore visitors' different comfort votes could also be observed.

On this other hand, the result could also be explained by visitor's adaptation to the local micro-meteorological conditions, which is that longer stay may cause people to be more tolerant to coldness. To further quantify this assumption, for each group, respondents' MTSVs were calculated for each 1K PET class, and linear regressions were conducted. All 4 groups showed acceptable correlation (R^2 between 0.3 and 0.45, $p < 0.05$), and the neutral PET for the "<15 min" group was 26.8 °C, and for the other 3 groups were between 20 and 22 °C, confirming that people exposed to coldness for a longer period may have a tolerance of coldness about 5K (PET) lower than people exposed for a shorter period. Similarly, Fig. 12 shows the percentage distributions of TSVs for different groups of length of residence in Shanghai. The figure shows that there are significant differences between groups: people who have lived in Shanghai for shorter time tended to consider the environment as

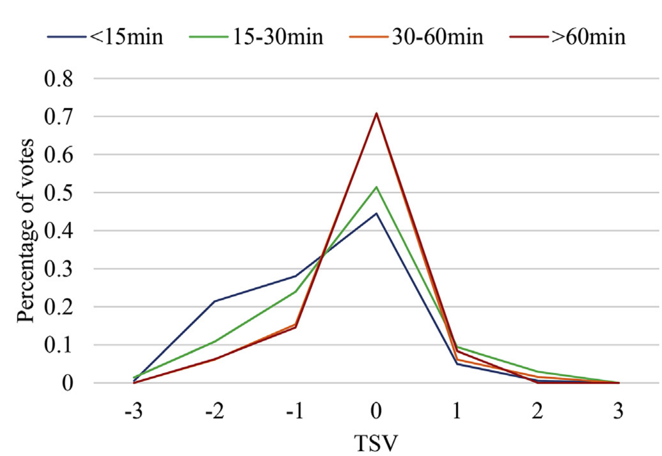

Fig. 11. Percentage distribution of TSVs for different groups of duration of stay.

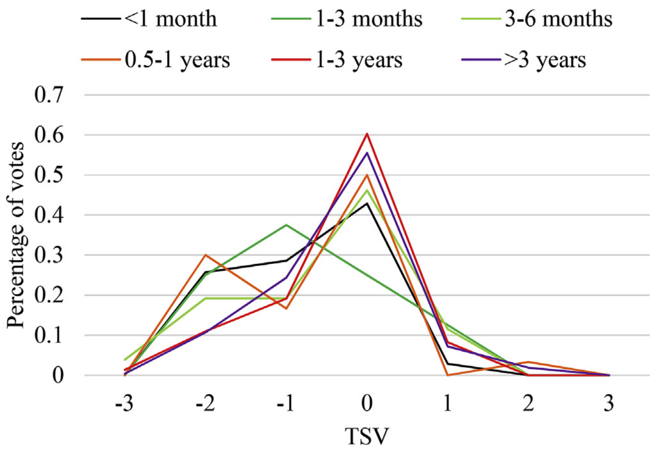

Fig. 12. Percentage distribution of TSVs for different groups of length of residence in Shanghai.

cold; on the other hand people who have lived in Shanghai for longer time (>1 year) got more adapted to the local weather condition, therefore had a larger tendency to consider the environment as neutral. Both short-term and long-term adaptations to the cold weather were observed in this case.

4.4. Micro-meteorological conditions and space use

To further examine the influence of the local micro-meteorological condition on visitors' space use, attendance count was compared against T_a, T_{mrt} and PET. Because the attendance count at the square was by unobtrusive observation, therefore it was impossible to collect person data for each individual, such as age, weight and height. Instead an alternative approach was taken which used a "standard" person for PET calculation (male, 35 years old, 1.75 m tall, 75 kg weight, with a clothing index of 0.9 clo for autumn and 1.0 clo for winter, and an activity rate of 80 W). Fig. 13 shows the correlation between attendance count and three micro-meteorological factors, i.e., T_a, T_{mrt} and PET for autumn and winter. The correlation shows that the micro-meteorological condition affected visitors' attendance differently in autumn and winter. In autumn when the weather was moderate, i.e., T_a around 20 °C, T_{mrt} 33–43 °C, and PET 20–26 °C, attendance count showed no correlation with these micro-meteorological factors, suggesting that visitors' space use were not necessarily affected by different micro-meteorological conditions. On the other hand, in winter when the weather was cold, i.e., T_a 5–15 °C, T_{mrt} 14–35 °C, and PET below 16 °C, attendance count showed positive relationship with all three micro-meteorological factors, with the strongest relationship with T_{mrt} ($R^2 = 0.43$), followed by T_a ($R^2 = 0.39$); the positive relationship with PET was not very significant ($R^2 = 0.16$). The result indicates that in winter, sunshine exposure and warm weather are important factors that affect visitors' use of outdoor space. The weaker correlation with PET indicates that a pure human-biometeorological index which is a combination of the effect of different micro-meteorological factors may not be suitable to be linked with park attendance: visitors tend to come to visit the park when the sunshine is good and the air temperature is high, perhaps regardless of the difference in wind speed and humidity. On the other hand, the result also reflects that people's perception to the outdoor environment is a complex issue with various dimensions including physical, physiological and psychological aspects, which need to be examined in more details in further studies in Shanghai.

5. Conclusions

In this study, questionnaire surveys and in-situ meteorological measurements in an urban park square in Shanghai were conducted in autumn and winter to investigate the thermal comfort of visitors and how space use was affected by micro-meteorological conditions. Computer tools were employed to simulate the spatial variation of the micro-meteorological conditions in the square. The human-biometeorological index of PET was used to assess visitors' objective thermal comfort sensation as determined by the local micro-meteorological factors. Seasonal differences were highlighted. The result showed that visitors' thermal sensations and space use were more significantly influenced by the micro-meteorological factors in winter as compared to autumn. In winter, visitors' subjective thermal sensations were positively related to air temperature and solar radiation, and the neutral PET range for Shanghai was 15–29 °C in winter, which is a much wider range as compared to tropical and high-latitude cities. This suggests

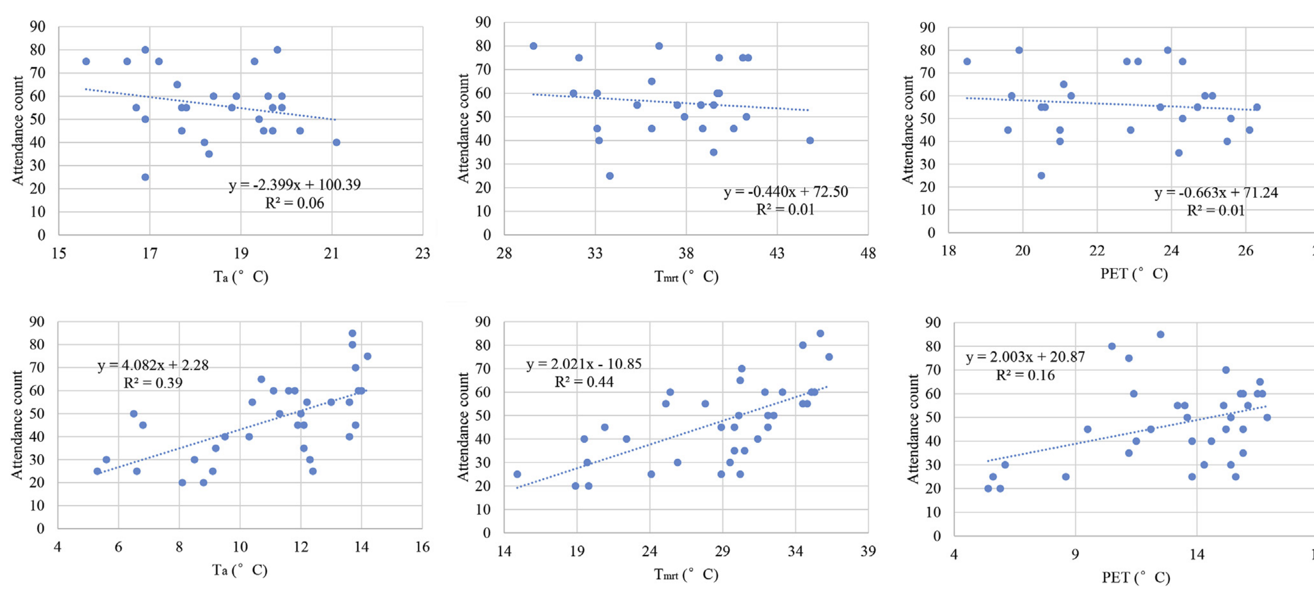

Fig. 13. Correlation between attendance count and T_a, T_{mrt}, and PET. The first row is for autumn, and the second row is for winter.

that citizens in Shanghai are exposed to more diverse weather conditions in winter with air temperature and humidity varying greatly, therefore are more tolerant to different micro-meteorological conditions. The study also found that air temperature and solar radiation are important factors in affecting outdoor space use in winter. This finding is especially helpful to understand attendance in parks and open spaces in winter when sun time is already short. In the present study, the studied square was surrounded by tall buildings located to the west, therefore the whole site was in the shadow casted by the buildings in the afternoon after 2:00 pm, which resulted in large decrease of attendance in the square. This suggests that the neighborhood of public open space should be carefully controlled in urban development and renewal practice, and only restrained development should be allowed in order to ensure sunshine provision and promote better use of the space. Also, facilities such as benches and kiosks will better entertain the visitors in winter if they are located at spots that have sufficient sunshine. The study also revealed visitors' thermal adaptation in winter. For example, longer duration of stay outdoors will cause the visitors to have a lower neutral PET value; and people who have lived in Shanghai for longer time also appeared to have higher tolerance to coldness. Furthermore, future studies should include more diverse sites with various micro-meteorological conditions to examine the influence of comfort on visitors' duration of stay. They should also include hot seasons to compare the seasonal difference of visitors' thermal comfort sensations and related behaviors. Based on these understandings optimized urban design strategies that are climate-sensitive and can improve thermal comfort and attract more visitors in different seasons could be developed.

Acknowledgment

This study is jointly supported by the National Natural Science Foundations of China NO. 41301087, NO. 41271055, and China Postdoc Foundation NO. 2013M540346. The authors would like thank the Shanghai Municipal Administration of Landscaping and City Appearance for providing plans of Zhongshan Park and also the facilities for carrying out surveys. The authors would also like to thank the two reviewers for the valuable, pertinent and detailed review comments which have completely overhauled the manuscript and turned it into a much better paper.

References

[1] J. Gehl, Life between Buildings : Using Public Space, sixth ed., The Danish Architectural Press, Copenhagen, Denmark, 2006.
[2] W.H. Whyte, City: Rediscovering the Center, Doubleday, New York, 1988.
[3] J. Jacobs, The Death and Life of Great American Cities, Penguin, Harmondsworth, 1972.
[4] J. Zacharias, T. Stathopoulos, H. Wu, Spatial behavior in San Francisco's plazas: the effects of microclimate, other people, and environmental design, Environ. Behav. 36 (2004) 638–658.
[5] J. Zacharias, T. Stathopoulos, H. Wu, Microclimate and downtown open space activity, Environ. Behav. 33 (2001) 296–315.
[6] L. Chen, E. Ng, Outdoor thermal comfort and outdoor activities: a review of research in the past decade, Cities 29 (2012) 118–125.
[7] T.-P. Lin, Thermal perception, adaptation and attendance in a public square in hot and humid regions, Build. Environ. 44 (2009) 2017–2026.
[8] I. Eliasson, I. Knez, U. Westerberg, S. Thorsson, F. Lindberg, Climate and behaviour in a Nordic city, Landsc. Urban Plan. 82 (2007) 72–84.
[9] M. Nikolopoulou, S. Lykoudis, Thermal comfort in outdoor urban spaces: analysis across different European countries, Build. Environ. 41 (2006) 1455–1470.
[10] K.S. Ahmed, Comfort in urban spaces: defining the boundaries of outdoor thermal comfort for the tropical urban environments, Energ Build. 35 (2003) 103–110.
[11] S. Thorsson, M. Lindqvist, S. Lindqvist, Thermal bioclimatic conditions and patterns of behaviour in an urban park in Goteborg, Int. J. Biometeorol. 48 (2004) 149–156.
[12] M. Nikolopoulou, S. Lykoudis, Use of outdoor spaces and microclimate in a Mediterranean urban area, Build. Environ. 42 (2007) 3691–3707.
[13] M. Oka, The influence of urban street characteristics on pedestrian heat comfort levels in Philadelphia, Trans. GIS 15 (2011) 109–123.
[14] Y. Zeng, L. Dong, Thermal human biometeorological conditions and subjective thermal sensation in pedestrian streets in Chengdu, China, Int. J. Biometeorol. 59 (2015) 99–108.
[15] H. Mayer, J. Holst, P. Dostal, F. Imbery, D. Schindler, Human thermal comfort in summer within an urban street canyon in Central Europe, Meteorol. Z. 17 (2008) 241–250.
[16] J. Holst, H. Mayer, Impacts of street design parameters on human-biometeorological variables, Meteorol. Z. 20 (2011) 541–552.
[17] H. Lee, J. Holst, H. Mayer, Modification of human-biometeorologically significant radiant flux densities by shading as local method to mitigate heat stress in summer within urban street canyons, Adv. Meteorol. (2013), http://dx.doi.org/10.1155/2013/312572 article ID 312572.
[18] M. Nikolopoulou, N. Baker, K. Steemers, Thermal comfort in outdoor urban spaces: understanding the human parameter, Sol. Energy 70 (2001) 227–235.
[19] 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.
[20] M. Nikolopoulou, K. Steemers, Thermal comfort and psychological adaptation as a guide for designing urban spaces, Energ Build. 35 (2003) 95–101.
[21] T.-P. Lin, K.-T. Tsai, C.-C. Liao, Y.-C. Huang, Effects of thermal comfort and adaptation on park attendance regarding different shading levels and activity types, Build. Environ. 59 (2013) 599–611.
[22] V. Cheng, E. Ng, C. Chan, B. Givoni, Outdoor thermal comfort study in subtropical climate: a longitudinal study based in Hong Kong, Int. J. Biometeorol. 56 (2012) 43–56.
[23] W. Yang, N.H. Wong, S.K. Jusuf, Thermal comfort in outdoor urban spaces in Singapore, Build. Environ. 59 (2013) 426–435.
[24] S. Thorsson, T. Honjo, F. Lindberg, I. Eliasson, E. Lim, Thermal comfort and outdoor activity in Japanese urban public places, Environ. Behav. 39 (2007) 660–684.
[25] F. Ali-Toudert, H. Mayer, Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate, Build. Environ. 41 (2006) 94–108.
[26] E. Ng, V. Cheng, Urban human thermal comfort in hot and humid Hong Kong, Energ Build. 55 (2012) 51–65.
[27] D. Lai, D. Guo, Y. Hou, C. Lin, Q. Chen, Studies of outdoor thermal comfort in northern China, Build. Environ. 77 (2014) 110–118.
[28] Shanghai Statistical Yearbook, China Statistics Press, Beijing, 2014, 2015.
[29] S. Thorsson, F. Lindberg, B. Holmer, I. Eliasson, Different methods for estimating the mean radiant temperature in an outdoor urban setting, Int. J. Climatol. 27 (2007) 1983–1993.
[30] F. Lindberg, B. Holmer, S.S.O.L.W.E.I.G. Thorsson, 1.0 – Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings, Int. J. Biometeorol. 52 (2008) 697–713.
[31] F. Lindberg, C.S.B. Grimmond, The influence of vegetation and building morphology on shadow patterns and mean radiant temperatures in urban areas: model development and evaluation, Theor. Appl. Climatol. 105 (2011) 311–323.
[32] H. Mayer, P. Höppe, Thermal comfort of man in different urban environments, Theor. Appl. Climatol. 38 (1987) 43–49.
[33] P. Höppe, The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment, Int. J. Biometeorol. 43 (1999) 71–75.
[34] N. Kántor, J. Unger, Benefits and opportunities of adopting GIS in thermal comfort studies in resting places: an urban park as an example, Landsc. Urban Plan. 98 (2010) 36–46.
[35] 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.
[36] L. Martinelli, T.-P. Lin, A. Matzarakis, Assessment of the influence of daily shadings pattern on human thermal comfort and attendance in Rome during summer period, Build. Environ. 92 (2015) 30–38.
[37] H. Lee, H. Mayer, D. Schindler, Importance of 3-D radiant flux densities for outdoor human thermal comfort on clear-sky summer days in Freiburg, Southwest Germany, Meteorol. Z. 23 (2014) 315–330.
[38] L. Chen, E. Ng, Simulation of the effect of downtown greenery on thermal comfort in subtropical climate using PET index: a case study in Hong Kong, Archit. Sci. Rev. 56 (2013) 297–305.
[39] A. Matzarakis, H. Mayer, Another Kind of Environmental Stress: Thermal Stress, WHO Collaborating Centre for Air Quality Management and Air Pollution Control Newsletters, 1996, pp. 7–10.
[40] T.-P. Lin, A. Matzarakis, Tourism climate and thermal comfort in Sun Moon Lake, Taiwan, Int. J. Biometeorol. 52 (2008) 281–290.