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Outdoor thermal comfort and activities in the urban residential community in a humid subtropical area of China

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ABSTRACT

A comfortable thermal environment is extremely important for the enjoyment of outdoor spaces. The relationship among microclimate, thermal sensation, and human behavior is expected to provide guidelines and implications for outdoor space design and planning practice. Given that, this study aimed at a better understanding of outdoor thermal comfort and activities in the residential community in a humid subtropical area of China. This study counted the number of people staying at the outdoor space, recorded physical measurements, and collected questionnaire surveys to determine the thermal comfort and activities of the outdoor space. Analysis results confirmed that the thermal experience and expectation existed and changed people's perceptions about the outdoor thermal environment in different seasons. The 90% acceptable physiologically equivalent temperature (PET) range affected by the local climate and thermal adaptation was 18.1–31.1 °C. The residents adapted to the outdoor spaces through adjustment of clothing, activity spaces and activity times in different seasons. These findings shed light on the optimal design of outdoor spaces for increasing the utilization rate. Sunny and shady subspaces should be considered to provide residents with more opportunities to interact with the environment for different seasons, thus improving their thermal comfort and the usage rate.

1. Introduction

A comfortable thermal environment is extremely important for the enjoyment of public spaces. Successful public spaces attract large numbers of people, which in turn attract business, workers, and residents, and the areas become economically profitable. The energy use of the surrounding buildings can also be affected. Finally, successful public spaces can benefit the city's reputation. However, planners and architects wishing to increase the quality of urban life by promoting the usage of public spaces are facing difficulties in assessing the effects of different design ideas on people's comfort and activities.

Preliminary studies have been conducted on the relationship among outdoor microclimate, outdoor thermal comfort and outdoor activity (Gehl [1]; Ishii et al. [2]; Li [3]; Nagara et al. [4]). These studies show that the response to the microclimate may be unconscious but often result in a different use of urban spaces in different climatic conditions. However, detailed microclimate analysis and thermal comfort assessments have been carried out only in the last decade because of advances of techniques in the fields of urban climatology and biometeorology, such as Montreal, Canada [5]; Cambridge, UK [6]; Gothenburg, Sweden [7,8]; Matsudo, Japan [9]; Taichung, Taiwan [10]; Huwei, Taiwan [11]; Athens, Greece [12]; Szeged, Hungary [13]; Tianjin, China [14]; Wuhan, China [15,16]; Hong Kong [17–19]; Sydney, Australia [20]; Taiwan [21]; and Tokyo, Japan [22]. Some studies in temperate regions [6–9,12] examined whether the number of people and the thermal environment were correlated, and demonstrated that the number of people using a space increased with increasing air temperature (Ta) or mean radiant temperature (T_{mrt}) in public spaces all year. In the subtropical regions, such as Taiwan [10,11,21], analytical results for the cool season were consistent with those acquired by studies of temperate regions, whereas, in the hot season as the values of thermal indices increased, the number of people visiting the squares decreased. In another subtropical city Wuhan China [15] the usage rate of outdoor space was maximized under the neutral sensation in autumn. These studies have revealed that people in different regions have different thermal requirements resulting from climate adaptation, and the levels of climate in a certain region affect local people's thermal adaptation strength.

Regarding research on outdoor thermal comfort, comfort indices are used to describe and assess it. At present, commonly used

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thermal comfort indices in the evaluation of the outdoor thermal environment can be divided into rational and empirical indices. The former is based on an analysis of the physics of heat transfer (i.e., based on the heat balance equation of the human body), such as the predicted mean vote (PMV) [23], standard effective temperature (SET*) [24], OUT_SET* [25], physiologically equivalent temperature (PET) [26,27], and universal thermal climate index (UTCI) [28]. The PMV and SET* indices have a solid basis for indoor use, whereas the OUT_SET*, PET and UTCI indices have been primarily designed for outdoor use [20]. Empirical indices are derived from subjective estimates. One example is the correlation between subjective thermal perception and measured meteorological variables determined through multiple regression analysis [29,30]. However, the validity of regression models are limited to the climate regions where the various data are obtained [29,30].

According to the literature reviewed above, outdoor thermal comfort in an urban environment is a complex issue with multiple layers of concern. The assessment framework should work on at least four levels: physical, physiological, psychological, and social/behavioral [6,20–22,31,32]. However, physiological adaptation to a climate is generally slow and has not been a focus of thermal comfort studies. Conversely, the impacts of psychological adaptation and behavioral adjustment on thermal comfort are significant [6,7,10,22,31–37]. Some studies have examined how psychological factors influence thermal comfort, indicating that the experience at a particular season in a particular space alter how a thermal environment is perceived [38,39], and the resident adjust their expectations in different seasons [10,14,18,19,21,40]. So the seasonal pattern is worth studying.

Over half of the world's population lives in cities [41], and much of it lives in residential communities, especially in China, with the highest population in the world. The outdoor space of the residential community is close to the residents' life. So the relationship among microclimate, thermal sensation, and human behavior in the residential communities is expected to provide guidelines and implications for outdoor space design and planning practice. However, detailed microclimate analysis and outdoor thermal comfort assessments were mostly carried out in the city squares, parks and campus in China [10,11,14,16–19]. The outdoor space designs, microclimates, thermal comfort and human behaviors in residential communities might be different with those of other urban spaces. The present study recognized this, and studied the relationships among microclimate, thermal comfort, and human behaviors in the outdoor spaces in residential communities in the humid subtropical area of China.

Given all of this, this study is expected to produce relevant and timely data to provide a better understanding of general outdoor thermal comfort and activity in the residential communities in different seasons in the humid subtropical area of China, and provide guidelines and implications for outdoor space design and planning practice.

2. Methods

2.1. Climate and sites

This study was conducted in Guangzhou, a typical city in the humid subtropical area of China. Guangzhou is located in the south of China at a longitude between 112.8°E and 114.2°E and latitude between 22.3°N and 24.1°N. The annual mean air temperature and humidity of Guangzhou are 22 °C and 77%, respectively [42]. The monthly mean air temperature varies slightly throughout the year, with a range of 13–29 °C (Fig. 1). The monthly mean relative humidity is higher than 60% all year, and April is the wettest month, with a relative humidity of 84.5%. The daily mean air temperatures are 26–32 °C in July and 7–20 °C in January.

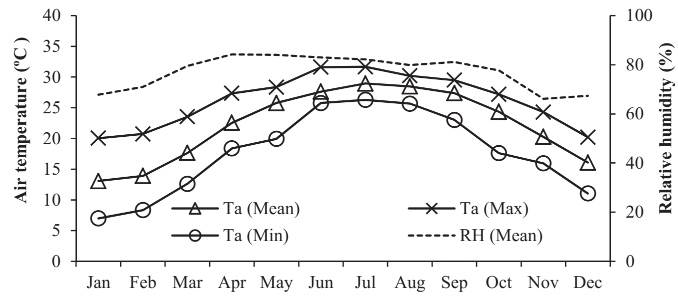


Fig. 1. Monthly mean air temperature ($Ta_{(Mean)}$), maximum air temperature ($Ta_{(Max)}$), minimum air temperature ($Ta_{(Min)}$), and mean relative humidity ($RH_{(Mean)}$) in Guangzhou [42].

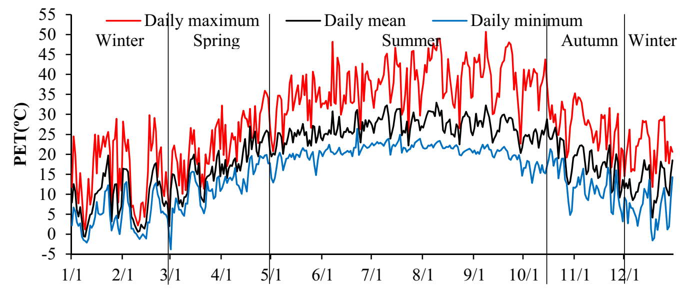


Fig. 2. Daily mean PET, maximum PET, and minimum PET in a typical year of Guangzhou.

The hourly PET was calculated accordingly based on the meteorological data of Guangzhou [42]. The daily mean, daily maximum and daily minimum PET are shown in Fig. 2. Based on the PET as the most key factor influencing people's evaluation of climate in urban and regional planning [26], the seasons could be defined as spring from Mar to Apr, summer from May to mid-Oct, autumn from mid-Oct to Nov, and winter from Dec to Feb. The summer is long, and the autumn is short.

The hourly PET is shown in Fig. 3. According to the assumption that the 90% acceptable PET range (21.3–28.5 °C) [10] obtained in Taiwan for an entire year in the same climate region is applied in Guangzhou, we could conclude that autumn is the most acceptable season, with 42% '90% acceptability', followed by summer and spring, with 33% and 28%, respectively; winter is the most unacceptable season, with 8% '90% acceptability'. The ultimate goal of this study is to provide guidelines and implications for outdoor space design and planning practice to improve the outdoor environment and maximize outdoor usage. Thus, in this work, we focused only on the worse seasons: the hotter summer, the colder winter, and the most humid spring. The comfortable and short autumn was not surveyed.

In humid subtropical area of China the enclosed layout and the regular layout are the most common layouts in residential community planning [43], especially the enclosed layout which is the development trend in the layout of residential community planning, because of the adaptability to the humid subtropical climate [44]. So this study choose three enclosed layout residential communities ("A", "B" and "C") and one regular layout residential community ("D") as the study object, as shown in Fig. 4. The four residential communities also present the representative features of the residential communities in humid subtropical area of China: (1) They are all new high-rise residential communities that were largely built in the last decade; (2) They are all have high population density with a total of more than 5000 residents in every residential community; (3) All residential communities have a greening rate

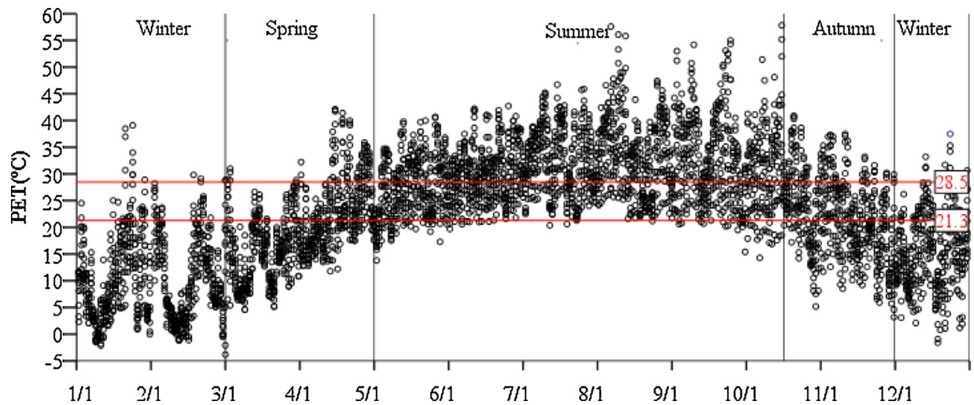


Fig. 3. Hourly PET in a typical year of Guangzhou.

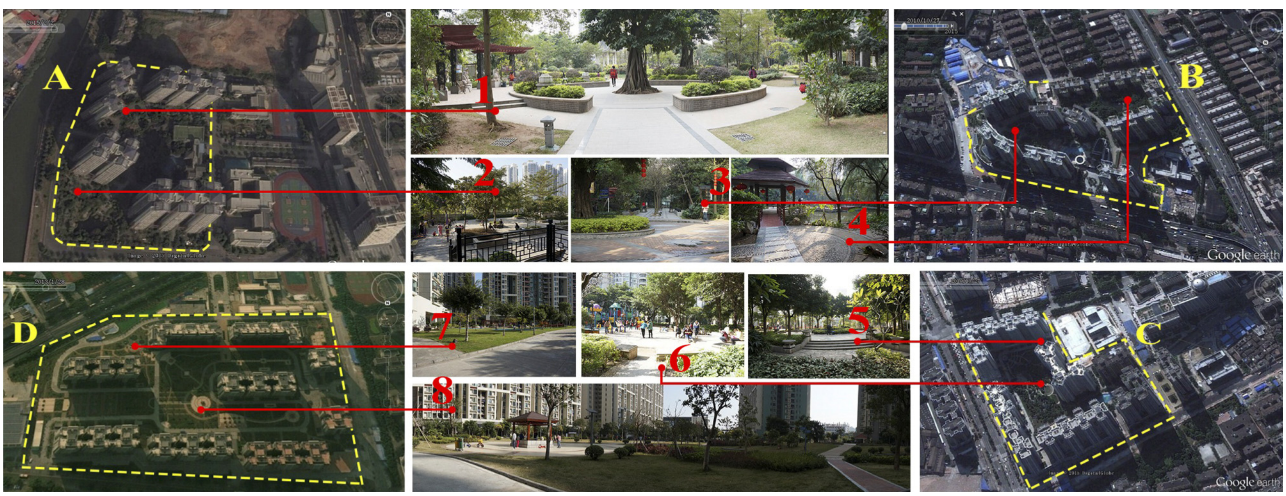


Fig. 4. Layout of the four residential communities investigated.

Table 1
Questionnaire of residents' main activity time.

The main periods of outdoor activities																
Weekday																
6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00
Weekend																
6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00

greater than 30%, with some activity spots for the outdoor activities. In this study, we were concerned with resting areas and focused on the two most popular activity spots in each residential community, as shown in Fig. 4.

2.2. Questionnaire survey

A questionnaire survey on outdoor thermal comfort and activities was carried out in the study. The first part of the questionnaire collected demographic information (i.e., age and gender), primary activity times of a day in the outdoor space (Table 1), reasons for visiting the particular place, clothing worn and activity level. The clothing of the respondents was recorded using the garment checklists extracted from ASHRAE Standard 55-2004 [45] and ISO Standard 7730 [46]. Table 2 shows the garment checklists and the clothing insulation (Clo) values of each item. Types of activity were recorded to determine the metabolic rates (M) of the subjects. Table 3 shows the types of activity and the metabolic rates of each type activity. The types of activity were set according to the major types of outdoor activity of residents in China, and the metabolic rates extracted from ASHRAE Standard 55-2004 and ISO Standard 7730. The second section asked subjects to rate their current thermal sensation, thermal comfort and thermal acceptability. The ASHRAE 9-point scales was used in the present study for thermal sensation, and the conventional scales were used for thermal comfort and acceptability (Fig. 5). Finally, subjects were asked to indicate their preferences for air temperature, sun, wind and relative humidity. The preferences for air temperature, sun, wind and relative humidity were collected by using 3-point scales (Fig. 6).

The questionnaire survey was carried out from January to September 2015, during the seasons of winter, spring and summer. Table 4 summarized the questionnaire surveys schedule on 24 days. The questionnaire surveys were performed during the timeframes of 8:00–12:00 and 14:00–18:00 in winter and spring, and 7:00–12:00 and 15:00–19:00 in summer, when the outdoor space was most frequently used. Each activity spot was visited once in an entire day in every season. All field surveys were carried out on days with suitable weather to avoid windy or rainy days. Two

Table 2
Garment checklists.

Upper Body	☐ Vest (No sleeves) 0.06 Clo;	☐ T-shirt (short sleeves) 0.08 Clo;	☐ Sweater 0.3 Clo;
	☐ Dress (No sleeves) 0.23 Clo;	☐ Shirt (Long sleeves) 0.15 Clo;	☐ Thin coat 0.36 Clo;
	☐ Dress (With sleeves) 0.29 Clo;	☐ Long underwear top 0.2 Clo;	☐ Thick coat 0.44 Clo;
Lower Body	☐ Long underwear bottoms 0.15 Clo;		☐ Shorts/skirt 0.1 Clo;
	☐ Long pants or long skirt(thin) 0.15 Clo;		
	☐ Long pants or long skirt(thick) 0.24 Clo;		
Feet	☐ Socks 0.02 Clo;	☐ Shoes 0.04 Clo;	☐ Sandals 0.02 Clo;

Table 3
Types of activity and metabolic rates.

What were you doing in the past 30 min prior to the survey?
☐ Seated (60 W); ☐ Standing (70 W); ☐ Strolling (115 W); ☐ Exercising (180 W); ☐ Babysitting (Seated) (100 W); ☐ Babysitting (Standing) (150 W);

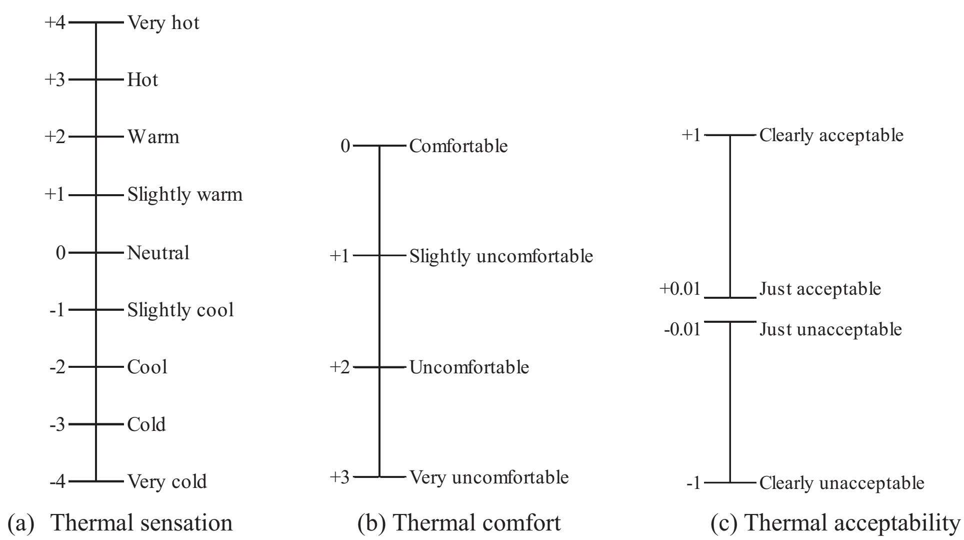


Fig. 5. Thermal sensation, thermal comfort and thermal acceptability rating scales.

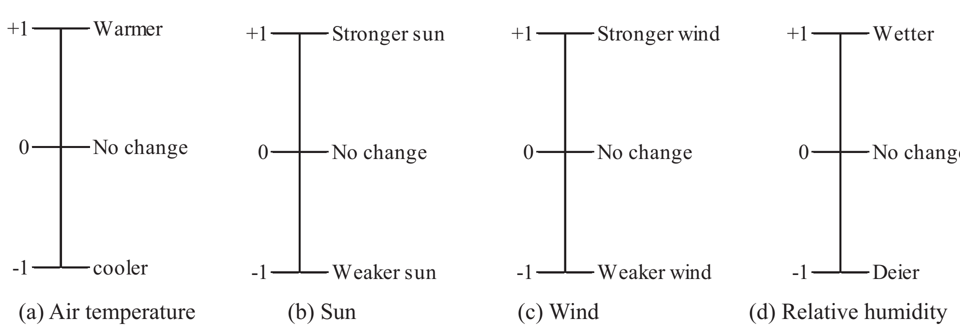


Fig. 6. Preference rating scales.

Table 4
Questionnaire surveys schedule.

Year	Season	Mon	Day	Hour	
				Physical measurements	Questionnaire survey
2015	Winter	Jan	10, 17, 19, 22, 25, 28	8:00–19:00	8:00–12:00 & 14:00–18:00
		Feb	2, 8	8:00–19:00	8:00–12:00 & 14:00–18:00
	Spring	Apr	4, 14, 16, 22, 23, 27	8:00–19:00	8:00–12:00 & 14:00–18:00
	Summer	Jun	20, 22, 27, 28	7:00–20:00	7:00–12:00 & 15:00–19:00
		Aug	2, 6, 19, 22	7:00–20:00	7:00–12:00 & 15:00–19:00
		Sept	6, 11	7:00–20:00	7:00–12:00 & 15:00–19:00

spots were not surveyed in spring because of continuous rainy days, and two spots were surveyed twice in summer. The study obtained a total of 1005 valid questionnaires: 305 in winter, 216 in spring, and 484 in summer.

The activities of people in the spot were recorded by high-resolution photographs taken from a fixed angle at 30 min intervals when the questionnaire survey was carried out. The activities of people were ex-post analyzed using the photographs.

2.3. Physical measurements

The physical parameters (i.e., air temperature (Ta), relative humidity (RH), global radiation (G), wind speed (v) and globe temperature (Tg)) next to the interviewee were measured during the questionnaire surveys. All instruments were compliant with the ISO 7726 [47] standard (Table 5) and placed at a height of 1.1 m above the ground, the recommended height of the sensors for standing subjects according to the ISO 7726, which represents the center of gravity of the human body. The air temperature and humidity probes were shielded from solar radiations with forced ventilation. On the measurement day, the microclimate parameters were acquired at 1 min intervals from 8:00 to 19:00 in winter and spring, and from 7:00 to 20:00 in summer (Table 4).

To determine the mean radiant temperature (T_{mrt}), the following formula was used. Where: Tg is the globe temperature (°C), Va is the wind speed (m/s), Ta is the air temperature (°C), D is the globe diameter (m), and ε is the emissivity of the globe.

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.10 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} \left(T_g - T_a\right) \right]^{0.25} - 273.15 \quad (1)$$

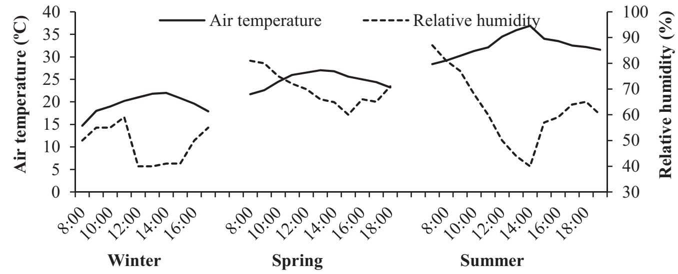
2.4. Outdoor thermal comfort index

PET was chosen as the outdoor thermal comfort index for the following reasons. First, the PET has been used previously in other regions for assessing the outdoor thermal environment. Thus, we can compare the results of this study with those of other regions. PET derives from the Munich Energy Balance Model for Individual (MEMI), which is a heat balance model of the human body. Its calculation assumes constant values for clothing (0.9 Clo) and activity (metabolic rate of 80 W). PET is already included in German VDI 3787 [26] for human biometeorological evaluation of climate in urban and regional planning. Furthermore, the PET has been proven to preferably generate accurate predictions for outdoor thermal comfort [48,49]. Third, the evaluation of the PET is very flexible and practical using free software packages (i.e., RayMan) [50]. The PET can be estimated by importing the measured micrometeorological data. Therefore, the PET was chosen as the primary thermal index in the present study.

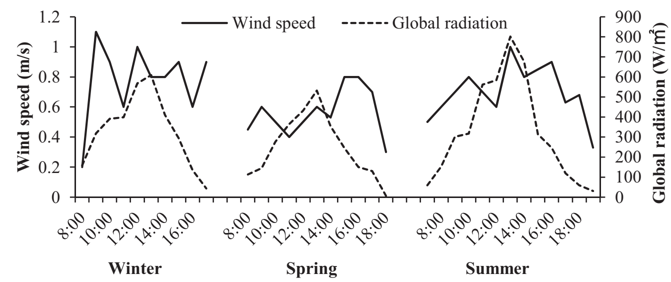
3. Outdoor thermal environment

The hourly mean air temperature, relative humidity, wind speed and global radiation of the outdoor spaces of the residential communities during the survey period were calculated in each season, and their changes are shown in Fig. 7. The ranges of air temperature were 15–22 °C in winter, 22–27 °C in spring and 28–37 °C in summer. The maximum of air temperature occurred at 14:00 in each season. The hourly mean relative humidity changed inversely to air temperature in each season, with the ranges of 41–59% in winter, 60–81% in spring, and 40–87% in summer. The relative humidity was highest in spring (70% on average) and lowest in winter (40% on average). The wind speed remained at an average level of 0.5 m/s in each season. The global solar radiation was strongest in summer, followed by winter, and was weakest in spring, reaching its daily maximum at 13:00 in each season.

The T_{mrt} and PET were calculated according to Fig. 8. The hourly changes of T_{mrt} and PET were consistent with those of global solar radiation in each season. T_{mrt} and PET were highest in summer.



(a) Air temperature and relative humidity



(b) Wind speed and global radiation

Fig. 7. Hourly mean air temperature, relative humidity, wind speed and global radiation in each season.

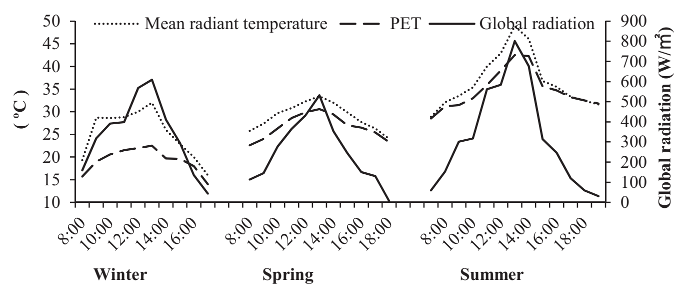


Fig. 8. Hourly mean radiant temperature (T_{mrt}), PET and global radiation in each season.

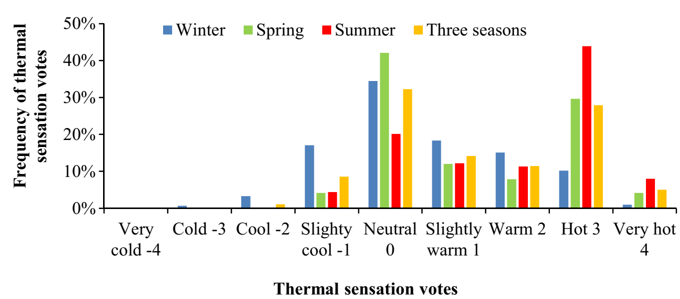


Fig. 9. Frequency distributions of thermal sensation votes.

T_{mrt} in spring was close to that in winter, especially during the time period of 10:00–15:00; however, PET was higher in spring than winter, mainly because of the high air temperature and high relative humidity in spring.

4. Outdoor thermal comfort

4.1. Thermal sensation and neutral PET

Fig. 9 shows the frequency distribution of the thermal sensation votes for all seasons and for each season. The votes with the highest frequency were 'Neutral' (34.4%) in winter, 'Neutral' (42.1%) in

Table 5
Metrological properties of instruments used.

Physical quantity	Instrument	Range	Accuracy
Air temperature	HOBO Pro V2 U23-001	−40 to 70 °C	±0.2 °C
Relative humidity	HOBO Pro V2 U23-001	0–100%	±2.5%
Global temperature	HD32.3	−10 to 100 °C	±0.5 °C
Wind speed	HD32.3	0–5 m/s	±0.05 m/s (0–1 m/s) ±0.15 m/s (1–5 m/s)
Global radiation	LP 471 PYRA 02.5	0–2000 W/m^2	±3%

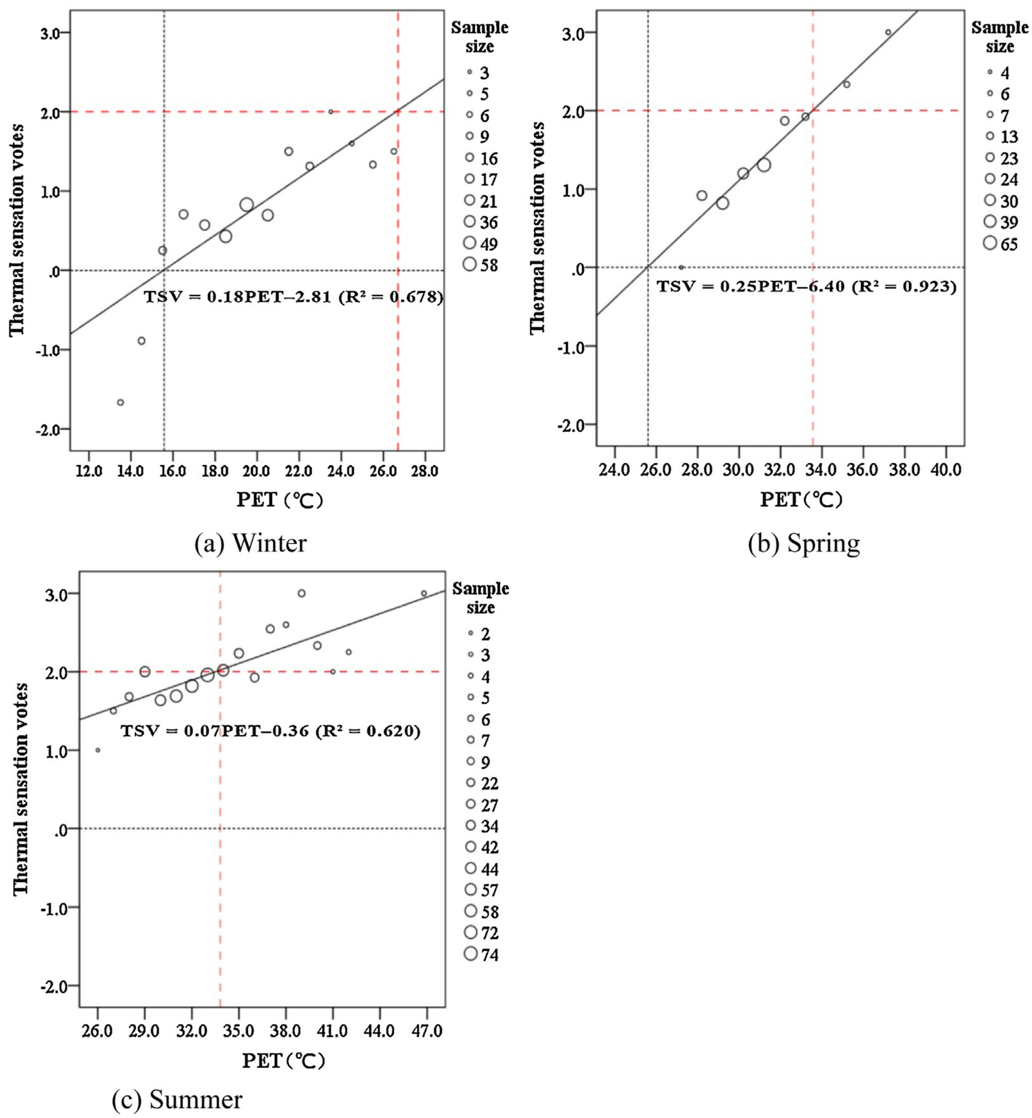


Fig. 10. Relationship between the mean thermal sensation votes and PET in each season.

spring, and 'Hot' (43.9%) in summer. For three seasons, the highest frequencies of votes were 'Hot' and 'Neutral', with a total of 60.1%, and the 'Cool', 'Cold' and 'Very cold' votes had few occurrences, with a total of 1.7%.

To establish a thermal sensation range for the humid subtropical area of China, the mean thermal sensation votes of respondents in each 1 °C PET interval group were calculated, and the relationships between the mean thermal sensation votes and PET were plotted for each season, as shown in Fig. 10.

In the process of regression, all the samples were embodied in the regression formula by sample size weighted regression. In some case, there were few samples sizes. The reason for the few sample sizes was that the questionnaire surveys were carried out on people who were present at sight in each season. People who found the environment to be unacceptable were unlikely to be there, such as at high PET in summer and at low PET in winter. The fitted regression lines for subject sensations versus PET are as follows:

$$\text{Forwinter}: TSV = 0.18PET - 2.81(R^2 = 0.678) \quad (2)$$

$$\text{Forspring}: TSV = 0.25PET - 6.40(R^2 = 0.923) \quad (3)$$

$$\text{Forsummer}: TSV = 0.07PET - 0.36(R^2 = 0.620) \quad (4)$$

The change slopes of the thermal sensation with PET were 0.18, 0.25 and 0.07 (corresponding to 5.5 °C PET, 4 °C PET, and 14 °C PET per sensation unit, respectively). The respondent thermal sensation was most sensitive in spring, followed by winter, and was least sensitive in summer. The neutral PET was determined to be 15.6 °C in winter, which was much lower than that in spring (25.6 °C). There was no neutral PET obtained in summer because the mean thermal sensation votes of respondents were between +1 and +3. The PETs corresponding to a ‘Warm’ sensation were therefore obtained for each season as 26.7 °C in winter, 33.6 °C in spring and 33.8 °C in summer. The ‘Warm’ sensation PET was much lower in winter, although the values were very similar in spring and summer.

4.2. Thermal comfort and comfortable PET

Fig. 11 shows the frequency distribution of the thermal comfort votes. The comfortable vote had the highest frequency in each season, with 67% in winter, 68% in spring, and 52% in summer. The largest frequency of ‘Hot’ votes (43.9%) in summer caused the frequency of summer comfortable votes to be approximately 15% less than those in winter and spring. The frequencies of slight uncomfortable, uncomfortable and very uncomfortable votes in the three seasons were 31%, 6% and 1%, respectively, which indicates that the majority of people (62%) found the outdoor thermal conditions to be comfortable.

Similar to the method used to calculate the thermal sensation range for PET, the mean thermal comfort votes (TCV) of respondents in each 1 °C PET interval group in every season were calculated and plotted as shown in Fig. 12. Good second-order polynomial relationships were found in winter and spring. The most comfortable PETs in winter and spring were 18.8 °C and 30.0 °C, respectively, which were 3.2 °C and 4.4 °C higher than the neutral temperatures, respectively. However, in summer, a good linear relationship was found, showing that the respondents felt more comfortable with lower PET.

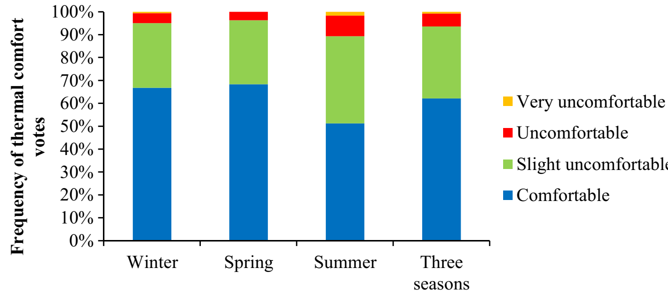


Fig. 11. Frequency distributions of thermal comfort votes.

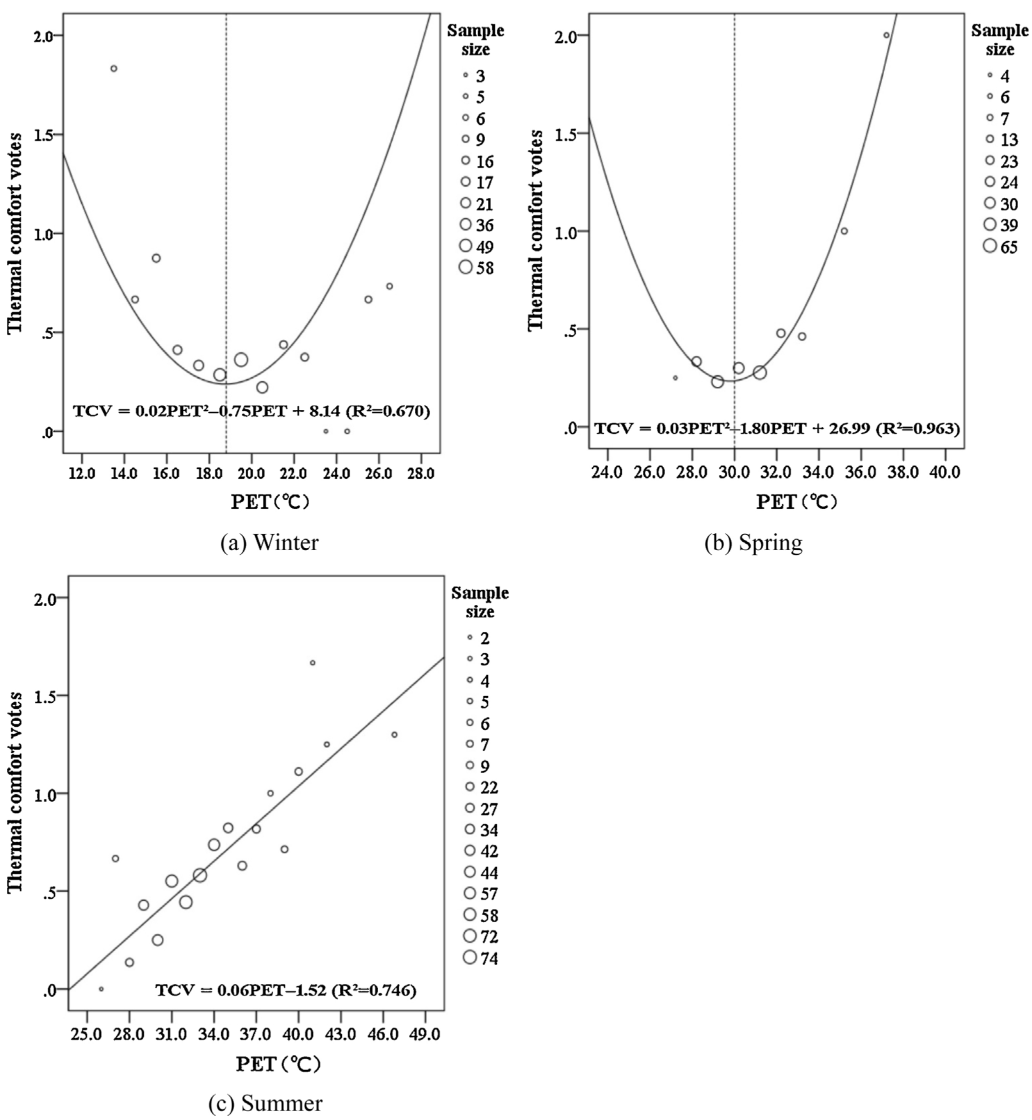


Fig. 12. Relationship between the mean thermal comfort votes and PET in each season.

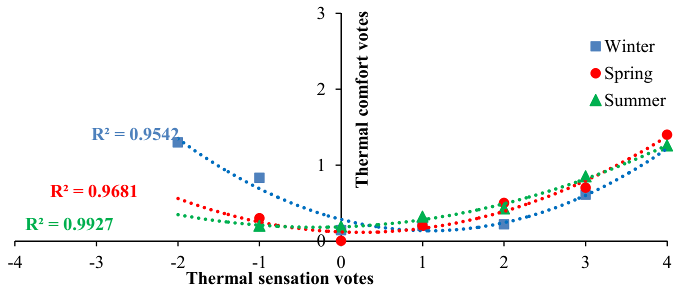


Fig. 13. Relationship between thermal sensation and overall comfort in each season.

The relationship between thermal sensation and overall comfort was established through regression. Good second-order polynomial relationships were found in three seasons shown as Fig. 13. The fitted regression formulas for different seasons are as follows. The result shows that in winter, the "slightly warm" sensation (TSV = 1) was much more comfortable than the "neutral" sensation (TSV = 0); in spring, people preferred warm conditions (the most comfortable sensation was 0.2); in summer, the "slightly cool" sensation (TSV = –0.3) was the most comfortable.

$$\text{Forwinter}: \text{TCV} = 0.1275\text{TSV}^2 - 0.2766\text{TSV} + 0.2846(R^2 = 0.9542) \quad (5)$$

$$\text{Forspring}: \text{TCV} = 0.0893\text{TSV}^2 - 0.0421\text{TSV} + 0.1186(R^2 = 0.9681) \quad (6)$$

$$\text{Forsummer}: \text{TCV} = 0.0584\text{TSV}^2 + 0.0360\text{TSV} + 0.1858(R^2 = 0.9927) \quad (7)$$

4.3. Thermal acceptability

To account for subject thermal unacceptability under different temperatures of PET in each seasons, the thermal unacceptable rate in each 1 °C PET interval group were calculated and plotted. Similar to the method used to calculate the thermal sensation range for PET, the mean unacceptable rates of respondents in each 1 °C PET interval group in every season were calculated. Unacceptable rate is defined as the proportion of the unacceptable vote accounted for the total votes [46]. The unacceptable rates of respondents in each 1 °C PET interval group were calculated based on this concept. The group with very small sample size (i.e. less than 10) was abandoned, because the unacceptable rate was not typical and representative.

Fig. 14 plots the thermal unacceptable rate in each 1 °C PET interval group in each season. Similar results to the relationships between thermal comfort votes and PET were obtained, showing second-order polynomial relationships in winter and spring and a linear relationship in summer. The 90% acceptability (10% unacceptability) ranges and corresponding thermal sensation vote ranges are shown in Table 6. According to the ASHRAE Standard 55 specification that acceptable thermal conditions must be acceptable at minimum 90% of occupants in a space (i.e., ≤10% of occupants feel unacceptable) when a high standard is applied [45], the 90% acceptable TSV ranges were 0.2–1.3 in winter, 0.6–1.7 in spring, and ≤1.9 in summer.

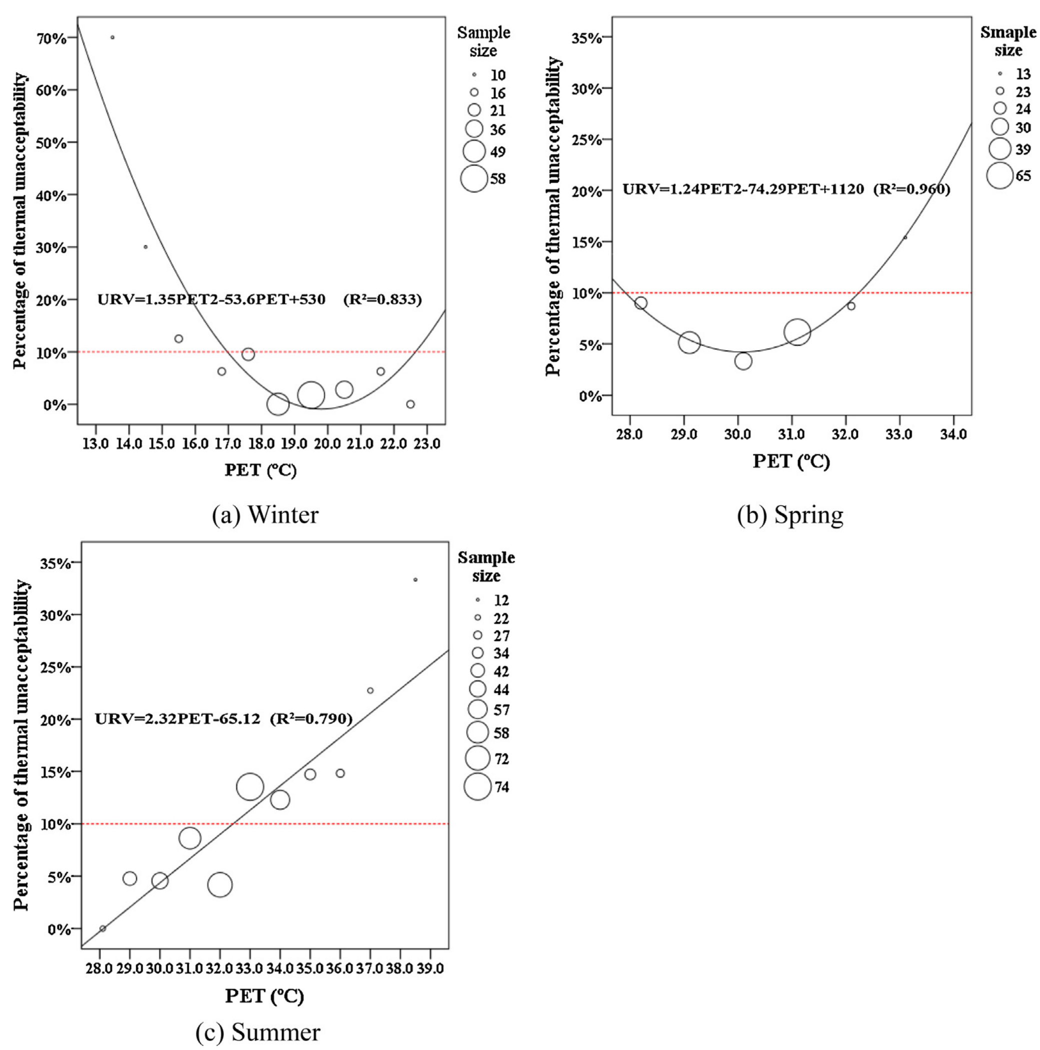


Fig. 14. Relationship between the thermal unacceptable rate and PET in each season.

Table 6
The 90% acceptability ranges of PET in each season.

Season	90% acceptability PET (°C)	90% acceptability TSV
Winter	16.9–22.7	0.2–1.3
Spring	27.9–32.3	0.6–1.7
Summer	≤32.4	≤1.9

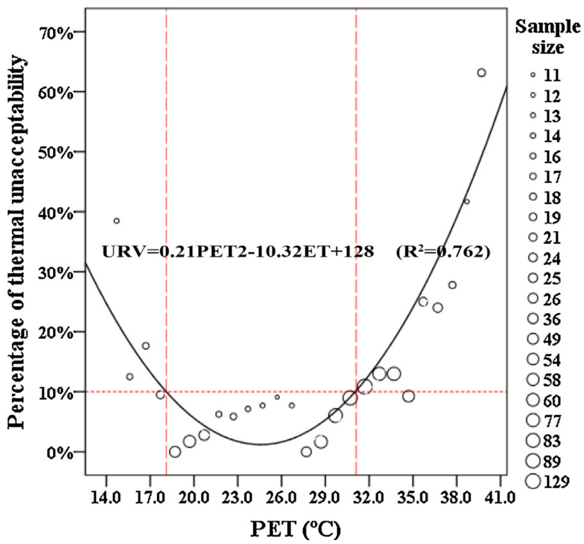


Fig. 15. Relationship between the thermal unacceptable rate and PET in all seasons.

Lin [10] found that in the humid subtropical area of Taiwan with the monthly mean air temperature of 13–29 °C, the 90% acceptable range for an entire year was 21.3–28.5 °C PET, which was significantly higher than the middle European scale of 18–23 °C PET [48] (in the temperate regions, with the monthly mean air temperature of 2–20 °C). The relationship between the thermal unacceptable rate and the PET in all seasons in Guangzhou is shown in Fig. 15. The 90% acceptability (10% unacceptability) range was 18.1–31.1 °C PET. The thermal acceptable range in Guangzhou was much higher than the middle Europe (18–23 °C) and similar to that in Taiwan (21.3–28.5 °C).

4.4. *Sources of discomfort*

In order to identify sources of discomfort, analysis was carried out on the preference for thermal environmental factors of overall uncomfortable respondents as voted slightly uncomfortable, uncomfortable and very uncomfortable (1, 2 and 3) in each season. Fig. 16 presents the different evaluation categories of the preference for the different seasons. The analysis for humidity preference in each season indicated that no significant variance existed regarding whether uncomfortable people prefer low or high humidity and the humidity wound not lead discomfort. In contrast, the air temperature, sun and wind would lead discomfort with the seasons. In winter, weak sunshine and strong wind were associated with discomfort. Whereas, in spring and summer, low wind speed and high air temperature were sources of discomfort. Additionally, in summer strong sunshine was associated with discomfort. In different seasons different microclimatic parameters were associated with discomfort.

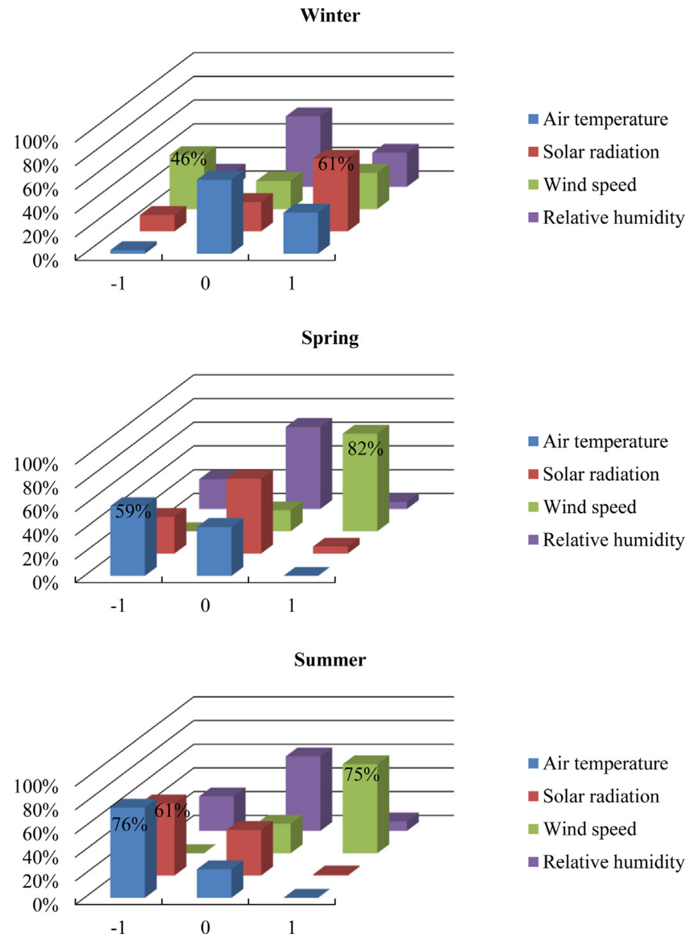


Fig. 16. Percentage distribution of preference for thermal environmental factors of overall uncomfortable respondents.

Table 7
Average values of activity and clothing in all research sites during different seasons.

Site	Activity (average) (W)			Clothing (average) (Clo)		
	Winter	Spring	Summer	Winter	Spring	Summer
1	105	99	107	1.15	0.82	0.41
2	103	109	113	1.04	0.64	0.42
3	97	–	104	1.05	–	0.38
4	102	–	107	1.04	–	0.39
5	105	109	94	0.97	0.75	0.37
6	112	117	108	1.08	0.81	0.36
7	110	99	117	0.94	0.89	0.41
8	105	98	101	1.07	0.8	0.40

5. Behavioral adjustments

5.1. *The role of activity and clothing*

Table 7 shows the average values of activity level and clothing insulation in all research sites in different seasons. Generally, very small differences were found between areas and seasons in terms of people's activity, the reason being that, the people were mainly sitting, standing or strolling in each season. These actions represented the typical daily behavior of the people in Guangzhou in the outdoor spaces. On the other hand, the respondents' clothing changed with the seasons, with most heavy in winter, followed by spring and lightest in summer.

In compliance with ISO 7730 [46], average values of the interviewees' clothing varied between 0.31 Clo and 1.41 Clo (average 0.65 Clo), with the lower average values in summer (0.40 Clo) and the

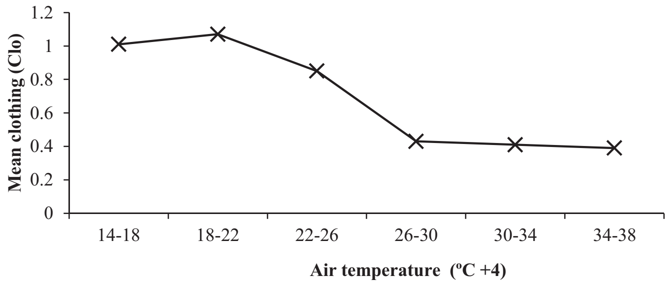


Fig. 17. The effects of air temperature on mean clothing level.

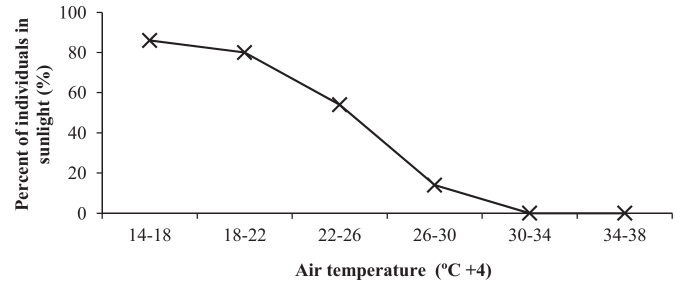


Fig. 19. The percent of individuals in sunlight.

higher values in winter (1.05 Clo). Fig. 17 shows the mean clothing levels at different air temperature ranges. The subjects changed their clothing from heavy ones (1.05 Clo) to light ones (0.40 Clo) with the increase of air temperature from 14 to 18 °C up to 34–38 °C. When the air temperature in the range of 14–22 °C (for winter) and 26–38 °C (for summer), the mean clothing remained the same, with 1.05 Clo and 0.4 Clo respectively.

5.2. Activity spaces

The features of spatial distribution of outdoor activities in different seasons are shown in Fig. 18. From the features of spatial distribution, we can see that the residents adapted to the outdoor space through behavioral adjustment in different seasons. In winter, the residents preferred activity in the sunlit areas. In winter, even the residential roadways designed for cars in the sunlight would be chosen as the activity areas. In spring, the residents preferred activity in the border space of sunlight and shade, so the residents could quickly adapt to the outdoor environment by changing their personal location. In the summer, the residents preferred activity in the sunshade. The features of spatial distribution conformed to the result of sources of discomfort, weak sunshine was associated with discomfort in winter and strong sunshine in summer, and residents chose the comfort space for activities.

Fig. 19 shows the percent of individuals in sunlight across all research sites in the whole survey. More than 80% of the individuals were in sunlight at low temperature range with 14–22 °C, the situation occurred mainly in winter. Whereas, the proportion decreased as the air temperature increased. Only in spring at the range of 22–26 °C there was an equal distribution of individuals in the shade and in the sun, indicating that this was the temperature at which most people would find it equally comfortable to do so, in shade or sun. A much smaller percentage was in the sunshine at high temperatures in summer.

Fig. 18. Features of spatial distribution of outdoor activities in each season.

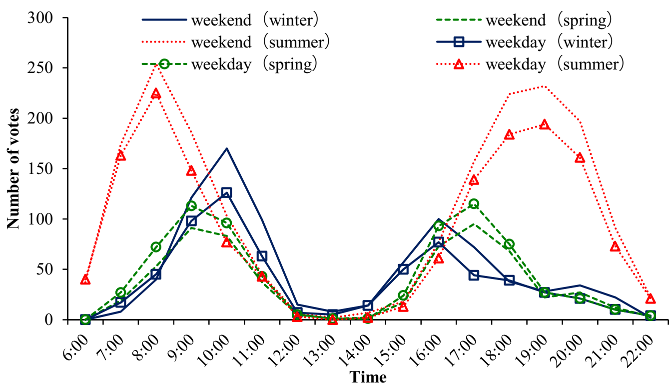


Fig. 20. The main activity time in each season.

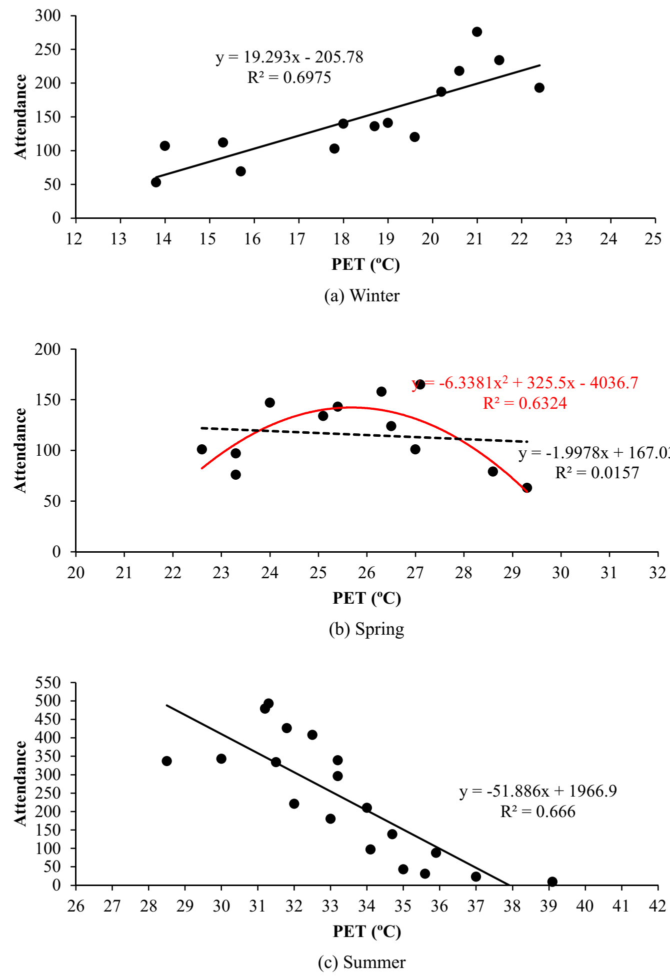


Fig. 21. Relationship between PET and attendance in each season.

5.3. Activity times

The main activity times in different seasons are shown in Fig. 20. The activity time was affected by the daily life patterns of the residents. For example, residents often went home for lunch and took a nap afterward, resulting in a significant decrease in the number of people outside from 12:00 to 14:00 in each season. The activity times were basically similar on weekends and weekdays in each season. In contrast, there was seasonal variation in the diurnal distribution of the activity times in the outdoor space. In summer, the times of maximum attendance were in early morning (8:00–9:00) and evening (18:00–19:00). Attendance increased significantly as it became dark. In spring, the highest activity of people was normally in the mid-morning period (9:00–10:00) and in the afternoon (17:00–18:00). In winter, attendance reached maximum levels at midday (10:00–12:00) and early afternoon (16:00–17:00).

As the seasons transitioned from winter to summer, the time of maximum attendance moved from midday and early afternoon toward the early morning and evening. The corresponding solar radiation became weaker, and the temperature decreased (Fig. 7). The diurnal distribution of the activities in different seasons also confirmed the result of sources of discomfort, weak sunshine was associated with discomfort in winter and strong sunshine in summer.

5.4. Attendance

Fig. 21 shows the relationships between the number of people in the activity sites and PET based on 16 observations in winter, 12 observations in spring, and 20 observations in summer. Good linear relationships were found in winter and summer. In winter, the number of people in the outdoor space was strongly and positively correlated with the PET. Many people visited the outdoor space when the PET increased. In summer, the number of people in the outdoor space was strongly and negatively correlated with the PET; when the PET increased, relatively few people visited the outdoor space, whereas in spring, a good second-order polynomial relationship was found, showing that the attendance reached its peak in the range of 25–27 °C PET and gradually decreased as the environment became colder or warmer.

6. Discussion

6.1. Thermal sensation and neutral PET

In winter from Dec to Feb, the daily mean PET fluctuated greatly from −0.6 °C to 20 °C (Fig. 2), and it was the coldest season all year. The neutral PET and warm PET were 15.6 °C and 26.7 °C, respectively. With the transition of season from winter to spring (daily mean PET was 8–27 °C), the subjects increased their neutral PET to 25.6 °C and their warm PET to 33.6 °C. In summer, there was no neutral PET, and the warm PET was 33.8 °C. The comparison results indicated that people adjust their thermal perception with the seasons and residents enhanced their tolerance for hot environment in summer. The experience at a particular time in a particular space alters how a thermal environment is perceived [39]. Experiential factors were also found in other studies (Table 8). Similar results were reported in the studies of Tianjin [14], Taichung [10], Hong Kong [19], Rome [51] and Cairo [52], with the transition of season from winter to summer residents increased their neutral PET. On the other hand different results were obtained in the studies of Damascus [53] and Sydney [20], the neutral PETs in summer were lower than those in winter. In both studies, this phenomenon was explained through the concept of alliesthesia. It is a psychological mechanism which leads people to consider positively everything that warms them when the environment is cool and vice versa.

The change slopes of the thermal sensation with PET were 0.18 in winter, 0.25 in spring and 0.07 in summer (corresponding to the thermal sensitivity (PET/TSV) of 5.5 °C, 4 °C, and 14 °C, respectively). Based on these results, we concluded that residents' thermal sensation was more sensitive in winter than in summer. These indicated the experience altered how a thermal environment was perceived. Same phenomenon was also found in other studies, such as Tianjin [14], and Taichung [10] and Damascus [53] (Table 8), with 5.3 PET/TSV, 5 PET/TSV and 8.8 PET/TSV in winter, and 10 PET/TSV, 8.4 PET/TSV and 16.7 PET/TSV in summer. Whereas, different results were obtained in the studies of Hong Kong [19] and Rome [51],

Table 8
The neutral PET and the thermal sensitivity (PET/TSV) in other studies.

City	Location	Neutral PET [°C]		PET/TSV [°C]	
		Winter	Summer	Winter	Summer
Tianjin, China [14]	38.3°N, 116.4°E	9.2	15.6	5.3	10
Taichung, Taiwan [10]	24.1°N, 120.7°E	23.7	25.6	5	8.4
Hong Kong, China [19]	22.3°N, 114.2°E	21	25	8.4	7.3
Rome, Italy [51]	41.5°N, 12.3°E	24.9	26.9	8.5	5.9
Cairo, Egypt [52]	31.0°N, 31.3°E	26.5	27.4	–	–
Damascus, Syria [53]	33.6°N, 36.3°E	24.2	15.7	8.8	16.7
Sydney, Australia [20]	33.9°S, 151.2°E	28.8	22.9	–	–

with 8.4 PET/TSV and 8.5 PET/TSV in winter, and 7.3 PET/TSV and 5.9 PET/TSV in summer, respectively.

The thermal sensitivity of people is a complex issue with multiple layers of concern, such as the local climate, physical (activity and clothing), and psychological (experience and expectation). Whereas, in Guangzhou, past experience reminded the residents that summer was longer (from May to mid-Oct) and hotter (daily mean PET was 20.3–33 °C) (Fig. 2), which might lead a less sensitive thermal sensation in summer. Probably the site also had an influence on the results of thermal sensitivity in different seasons provided in the study of Cairo [52]. In the study of Cairo, outdoor thermal comfort surveys were carried out in nine different zones in the urban park during the hot and cold months. The site of Canopy had a 7.8 PET/TSV thermal sensitivity in winter and 8.5 PET/TSV thermal sensitivity in summer. On the other sites the ranges of per sensation unit were larger in winter than those in summer.

6.2. Thermal comfort and comfort PET range

In winter, the "Slightly warm" sensation (TSV = 1) was much more comfortable than the "Neutral" sensation (TSV = 0); in spring, people preferred warm conditions (TSV = 0.2); and in summer, the "Slightly cool" sensation (TSV = –0.3) was much more comfortable. Neutral was never the situation in which residents felt comfortable. The most comfortable PETs in winter and spring were 18.8 °C and 30 °C, respectively, which were 3.3 °C and 4.4 °C higher than the neutral temperatures, respectively. The residents preferred warm conditions in the winter. In the transition from winter to spring, people preferred warm conditions. However, the respondents felt more comfortable with the lower PET because of the longer and hotter summer. The seasonal thermal preferences found in this study agree with the studies by Lai [14] and McIntyre [40]. Lai found that the most comfortable conditions were at a TSV of 0.86 for the cold season, 0.08 for the shoulder season, and –1.07 for the hot season, and McIntyre found that the optimal sensation was biased toward warm in winter and cool in summer. These comparative results demonstrated the impact of expectations on respondents' thermal comfort.

The 90% acceptable PET range according to the whole survey was found to be 18.1–31.1 °C. Both the upper and lower boundaries of the range were about 3 °C wider than that in Taiwan (range of 21.3–28.5 °C) [10], but much higher than that in middle Europe (range of 18–23 °C) [48]. The residents in Guangzhou were exposed to hot summer and warm winter climates (monthly mean air temperature of 13–29 °C), similar to that of Taiwan (monthly mean air temperature 16–29 °C), which led them to have warmer acceptability PET ranges of 18.1–31.1 °C and 21.3–28.5 °C, respectively. The middle European study had a lower thermal acceptability PET range (18–23 °C) due to the colder climate (monthly mean air temperature 2–20 °C). These results show how people coming from different areas present different thermal requirements resulting from climate adaptation, and the levels of climate in a certain region affect local people's thermal adaptation strength.

Table 9
Results of comfort PET ranges.

City	PET comfort range [°C]	Monthly mean air temperature
Glasgow, Scotland [55]	9–18	2–20
Tianjin China [14]	11–24	–3 to 26
Rome, Italy [52]	21.1–29.2	7.2–24.1
Western/middle Europe [48]	18–23	2–20
Taichung, Taiwan [10]	21.3–28.5	16–29
Guangzhou, China (present study)	18.1–31.1	13–29

From this point of view, the results of the present research agree with the study of Salata in Rome [51]. In the study of Rome the comparison of comfort ranges calculated by assuming that the comfort range was the interval –0.5 to 0.5 of the ASHRAE 7-point scale (Table 9) was made among Glasgow, Scotland [54], Tianjin China [14] and Rome, Italy [51]. The highest monthly mean air temperature in Rome led them to have warmer comfort PET ranges of 21.1–29.2 °C. Since residents in Glasgow and Tianjin expose themselves to a wider and colder climate, with monthly mean air temperature 2–20 °C and –3 to 26 °C, the climate adaption lead them to have a wider and lower thermal sensation range with 8–18 °C and 11–24 °C, respectively.

Finally, we may mention that the neutral PET and comfort PET ranges in the present study were based on questionnaire responses of people who were present at sight. These values might not be able to represent the characteristic of all residents in this region. Whereas, the results could be compared with the other regions, because they were all took the same questionnaire survey method. It would be appropriate to standardize the experimental design (site selection, season and time period of the survey, number subjects to interview), instruments ((type and accuracy of instruments), and measurement methods to reveal regional characters of outdoor comfort.

6.3. Behavioral adjustments–the role of clothing

Clothing adjustment accordingly related to environment has been viewed as an adaptive behavior by many studies. Many studies have investigated the relationship between clothing and thermal environment. Andrade et al. [55] concluded in Lisbon that clothing values varied between 0.24 Clo and 1.75 Clo mainly as a result of seasonal and daily variations in air temperatures and wind conditions. Similarly, the studies of Nikolopoulou [35] in different countries in Europe, and that of Lin [10] in Taiwan, found a strong relationship between average air temperature and clothing. Yahia [53] in Damascus, Syria and Lin [10] in Taiwan also found that a strong relationship between PET and clothing, and concluded that changing clothing was one of the individual ways of thermal adaptation. As expected, the results of present study shown that the air temperature was a strong predictor of the mean clothing and the insulation value of people's clothing tend to decrease with increasing temperatures over the whole year. While, the clothing insulation values in each season were not changing with the air temperature. These were also verified in the study of Lin in Taiwan [10], in the hot season when the PET was >33 °C, the clothes worn by respondents remained at approximately 0.6 Clo.

6.4. Outdoor thermal environment and usage

In winter, the residents chased the sunlight. When the solar radiation was stronger in the midday and early afternoon (with an average of 350 W/m^2; see Fig. 7), the amount of people attendance was large. In summer, the residents preferred activity in the sunshade. Attendance increased significantly as it became dark in the evening and in the early morning. In the spring, the residents chose the moderate times, later than the summer and earlier than the winter. The choice of activities space and activities times can be seen as behavioral adjustment. The residents choose the specific spatial where the residents accept subjectively for activities. To understand the features of spatial distribution of outdoor activities, and conclusion the microclimate properties of the space, which are helpful for the planning of the residential community. The outdoor activities have some temporal distribution regularity. The planners should be understand the regularity to create the comfortable microclimate of specified time with correctly synthesize the sun, sunshade and wind, which can increase outdoor space utilization rate.

The seasonal variation in the diurnal distribution of the activity times in outdoor space confirmed that there was a relationship between the number of people attendance in the outdoor space and the local outdoor thermal environment. In winter, attendance in outdoor spaces increased with increasing PET. In summer, the number of people visiting the outdoor space decreased as the PET increased, and the residents chose early morning and evening for outdoor activities. In spring, the attendance reached its peak in the range of 25–27 °C PET, and it gradually decreased as the environment became colder or warmer. Furthermore, at the time of maximum attendance the thermal comfort vote was relatively higher, which was pointing out the effect of expectations in this framework. Once the residents had decided to come out and sit outside they had accepted various facts and were prepared to accommodate them.

The relationship between thermal environment and outdoor space usage has been studied in different climate zones. Lin [10] found that in Taiwan, when the values of thermal indices in the cool season were high, many people visited the square. However, during the hot season, when the values of thermal indices were high, relatively few people visited the square. The results in winter and summer considered the result of Lin. Lai [15] found that in Wuhan from August 20, 2011 to November 27, 2011, the usage rate of outdoor space was maximized under the neutral sensation, which the result in spring of this study resembled. However, all studies conducted in temperate regions indicated that as values of thermal indices increased, the number of people frequenting outdoor public spaces increased both in summer and in winter. These show that the outdoor thermal environment associated with thermal adaptation directly impacts the use of outdoor public spaces.

Occupancy was affected not only by the outdoor thermal environment but also by the daily life patterns of the residents. For example, residents often went home for lunch and took a nap afterward, resulting in a significant decrease in the number of people outside from 12:00 to 14:00, which was not a choice on the questionnaire.

6.5. Design strategy for outdoor spaces

To increase outdoor space utilization rates, space design must improve the microclimates of outdoor spaces to increase visitor thermal comfort and meet the psychological expectations and behavioral characteristics of space users in the humid subtropical area of China.

These findings shed light on the design of outdoor spaces for increasing utilization rate. In the process of residential planning, the space directly irradiated by the sun in winter and spring should be set to attract the residents and improve the utilization of outdoor space. However, in summer, the shaded areas should be created in outdoor space by planting numerous trees or constructing artificial shelters. The sunny and shady subspaces should be considered to provide residents with more opportunities to interact with the environment, thus improving their thermal comfort and the usage rate.

7. Conclusions

This study counted the numbers of people staying at the outdoor space of four residential communities in a humid subtropical area of China, recorded physical measurements, and collected questionnaire surveys to determine the thermal comfort of outdoor space. The purpose of the study was to examine outdoor thermal comfort and outdoor activity. The main conclusions are as follows.

1. The neutral PETs were 15.6 °C in winter and 25.6 °C in spring. However, there was no neutral PET in summer. The warm PETs were 26.7 °C in winter, 33.6 °C in spring and 33.8 °C in summer. The most comfortable PETs in winter and spring were 18.8 °C and 30 °C, respectively, which were 3.3 °C and 4.4 °C higher than the neutral temperatures, respectively. However, in summer, the respondents felt more comfortable with lower PETs.
2. In winter, the "slightly warm" sensation (TSV = 1) was much more comfortable than the "neutral" sensation (TSV = 0); in spring, people preferred warm conditions (TSV = 0.2); in summer the "slightly cool" sensation (TSV = −0.3) was much more comfortable. The individuals had different preferences for thermal environmental factors during different seasons.
3. The 90% acceptable TSV ranges were 0.2–1.3 in winter, 0.6–1.7 in spring, and $\leq$1.9 in summer. The 90% acceptable PET range in all seasons was 18.1–31.1 °C PET. The acceptable PET range was different from middle Europe (18–23 °C) and Taiwan (21.3–28.5 °C).
4. In winter, the residents preferred activity in sunlit areas. Attendance reached its maximum level at midday (10:00–12:00) and afternoon (16:00–17:00). In spring, the residents preferred activity in the border space of sunlight and shade, and the highest attendance of people was normally in the mid-morning (9:00–11:00) and in the afternoon (17:00–18:00). In summer, the residents preferred activity in the sunshade, and the times of maximum attendance were early morning (8:00–9:00) and evening (18:00–19:00).
5. In Guangzhou, many people visited the outdoor space when the PET increased in winter. However, during summer, when the PET increased, relatively few people visited the outdoor space. In spring, the attendance reached its peak in the range of 25–27 °C PET, and it gradually decreased as the environment became colder or warmer.
6. In the design of outdoor spaces, sunny and shady subspaces should be considered to provide residents with more opportunities to interact with the environment for different seasons, thus improving their thermal comfort and the usage rate.

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