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Studies on the Specificity of Outdoor Thermal Comfort during the Warm Season in High-Density Urban Areas

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Abstract: With the acceleration of urbanization in China, high density has become a significant feature of urban development. Although high-density development provides convenience, it also results in numerous environmental and climatic problems, such as the urban heat island effect, haze and extreme weather. These issues have reduced the comfort levels of the urban outdoor environment, led to increased energy consumption and had serious impacts on social development and the lives of residents. Improving the comfort of the outdoor urban environment is vital, especially in the current tendency for high-density urban developments. This paper focuses on a typical urban district in Shanghai, where we have gathered ambient meteorological data and human thermal sensation votes during spring and summer through monitoring and questionnaire research. Correlation analysis was conducted to examine the relationship between thermal sensation votes and comfort indexes (PET, UTCI). The findings indicated that the neutral PET during spring and summer was 22.30 °C and 24.55 °C, respectively, whilst the neutral UTCI was 18.75 °C and 26 °C, respectively, with the neutral temperature in summer being significantly higher than that in spring. Upon comparing the evaluation indices, it was found that the correlation between the UTCI and average thermal sensation votes was stronger; thus, the UTCI better represents people's thermal sensation in the Shanghai area. Finally, regression analysis demonstrated that the acceptable PET range for 90% of cases during both seasons in Shanghai is between 25.0 °C and 32.1 °C, and the UTCI range is between 24.2 °C and 27.7 °C. This study presents theoretical criteria for evaluating environmental thermal comfort, laying the foundation for practical paths to optimize urban design for climate responsiveness in high-density urban areas.

Keywords: high-density urban areas; outdoor thermal comfort; comfort indicators; seasonal differences

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1. Introduction

With the progress of urbanization, the high-density urban development model has intensified the urban heat island effect whilst simultaneously increasing the frequency of extreme weather events. As a venue for rest, socialization and healing, a healthy and comfortable outdoor environment can extend the duration of individuals' outdoor recreational activities and foster their physical and mental well-being [1]. Therefore, the outdoor microclimate and environmental comfort are critical factors that influence the vibrancy of a city. Additionally, the outdoor microclimate and comfort have a direct correlation with the indoor heating and cooling loads in buildings. Therefore, enhancing the microclimate and outdoor comfort can decrease building energy consumption and urban carbon emissions whilst promoting the intensive and ecological development of the city [2].

The ASHRAE Standard 55 proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers posits that thermal comfort refers to a condition of mind

that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. This definition encompasses two dimensions: the objective parameters of the thermal environment and the subjective personal aspects, including health, tolerance and adaptability [3]. All six factors shall be addressed when defining conditions for acceptable thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, air velocity and humidity (AHERAE, 2020) [4]. The first two factors are personal, and the last four are environmental attributes. Although these six factors are independent from each other, they work cohesively to influence human thermal comfort [5]. Therefore, the objective of thermal comfort index analysis is to amalgamate multiple meteorological parameters and human variables into a single index to depict thermal comfort concisely. According to the assessment method, the comfort indicators frequently used can be categorized as either steady-state heat transfer models or dynamic heat transfer models. Steady-state heat transfer models consist of Operative Temperature (Top) [6], Outdoor Standard Effective Temperature (OUT-SET), Predicted Mean Vote (PMV) and others. Dynamic prediction models include the Physiologically Equivalent Temperature (PET) [7] and Universal Thermal Climate Index (UTCI). The study employs the Physiologically Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) [8] as dynamic prediction models. The assessment of outdoor thermal comfort can be investigated through questionnaire surveys to determine its efficacy in validating theoretical predictions.

Numerous domestic and international studies have demonstrated that outdoor thermal comfort is adaptable to different geographical regions, necessitating the selection of appropriate evaluation indicators. Xi, T. [9] conducted a four-day empirical study at two measurement sites during the winter in the cold region of Harbin, to compare and analyze the predictive performance of the SET*, PET, and the UTCI, regarding the outdoor thermal comfort of university campuses in cold regions. They observed that the PET had a stronger correlation with the interviewees in cold regions during winter, thereby establishing its superior predictive value. Lai [10] assessed the suitability of several thermal indices, including the PMV, PET and UTCI, for analyzing outdoor thermal comfort in cold regions under various climatic conditions. The study was conducted using actual measurements and research data gathered in a park in Tianjin, China. It was concluded that the UTCI is a better predictor of outdoor thermal comfort, while the PMV tends to overestimate outdoor thermal sensation. Zafarmandi, S. [11] conducted research to investigate the most applicable thermal indices in Tehran's cold and hot seasons. The results confirm that the Predicted Mean Vote (PMV) and Physiological Equivalent Temperature (PET) indices are better predictors of semi-outdoor thermal comfort in summer and winter than the Universal Thermal Climate Index (UTCI) and New Standard Effective Temperature (SET*), respectively, highlighting the importance of considering accurate thermal indices in different seasons. Consequently, the applicability of the thermal indices in a given climatic region and for a given season need to be validated with a large amount of experimental data.

Different regions exhibit unique climatic conditions, and the concept of thermal comfort varies across different climate regions, because the locals have lived there for an extended period. Their clothing behavior, living customs and psychological expectations are gradually adjusted to the local climate. For instance, Nikolopoulou et al. [12] studied the outdoor thermal comfort conditions of 14 different cities across 5 European nations using techniques such as microclimate measurements and surveys, and the results showed that there is a variation over a 10 °C range of neutral temperatures in these areas. In the transition season, the neutral temperature range is wider for southern cities compared to northern cities. This could be attributed to the difference in behavior between the southern and northern cities, which is a result of experience of a different range of climatic conditions and a difference in sensitivity to heat and cold. Through a literature review, Feng, X. [13] discovered that the comfort range is higher in Asian regions than in European regions. It was also found that hot summer and warm winter regions (i.e., Guangzhou, Hong Kong, and Taiwan) exhibit higher ranges than colder regions (i.e., Tianjin and Harbin). Under the same temperature conditions, the cultural diversity and climatic background of urban places'

people also affect their thermal perception and comfort levels. Kenawy's research [14] in Melbourne found that during the summer months, people from Oceania and Antarctica are the least tolerant to heat stress. On the other hand, the people from southeast Asia, Sub-Saharan Africa, and southern and central Asia are the most tolerant of the heat stress. The opposite was true in winter. Liu, W. [15] observed that the level of thermal comfort in a specific area could vary throughout different seasons. In Changsha of China, for instance, the neutral PET values for the outdoor environment are 23.3 °C in summer and 14.9 °C in winter, respectively. Even if they are in the same area, the perception of thermal comfort varies among different groups of people. Yang, B. et al. [16] conducted empirical research in urban public spaces (two urban parks) in the city of Ümerö, Sweden, and the results of the study showed that, at the same UTCI value, the local residents showed a 0.1–0.5 higher subjective thermal sensation votes than non-local residents. Moreover, due to their higher activity levels, children's average thermal sensation votes were also higher than adults'.

In summary, the suitability of widely used thermal comfort indices varies among different climatic regions. Outdoor thermal comfort is influenced by a blend of meteorological and individual factors and also shows obvious geographical differences. The adaptability of thermal indices has been extensively validated [11–13,15,16]. In recent years, the PET and UTCI have been frequently used for assessing thermal comfort in Europe and the United States. However, China covers a large territory with different climate zones, and it is necessary to study and verify the applicability and the comfort range of these indices before they are used in China. Previous studies have examined the adaptability of thermal comfort in hot and humid regions like Guangzhou and Hong Kong, as well as in cold regions like Harbin and Tianjin; however, there is a lack of research on whether Shanghai, as a representative city of hot summer and cold winter areas, yields similar results. Shanghai is the largest city in China and represents a high-density urban area. In this article, our primary research objective is to compare and analyze the differences of the PET and UTCI in warm seasons to select appropriate thermal indices and find their comfort range for Shanghai and similar climate areas. The findings of this article will establish a foundation to assess the thermal comfort in the areas with summers as hot and winters as cold as Shanghai.

2. Method

2.1. Research Area

Shanghai is located in the subtropical monsoon climate region with hot summers and cold winters. The hot season lasts 3.0 months from 17 June to 15 September, with July being the hottest month, when the mean maximum temperature is 31 °C and the mean minimum temperature is 26 °C. The cool season lasts 3.2 months, from 5 December to 13 March, with mean daily maximum temperatures of 8 °C and mean minimum temperatures of 2 °C.

The campus of Tongji University was selected as a representative neighborhood in this study. The reasons why Tongji University was selected as the research area are as follows: From the perspective of urban function, the campus contains different functional zones such as dormitory areas, teaching areas, administrative areas and green areas, among others, making it compound and diverse in terms of functionality. The campus also features a variety of building heights, including high-rise buildings, multi-story buildings, and low-rise buildings. Additionally, the campus has a road traffic network with different functions and paving, such as carriageways and sidewalks. In terms of underlay material, the campus comprises a rich variety of green spaces, including hard paving, lawns, street trees, small woods and water bodies, making it resemble a miniature model of a city. It has unique advantages as a sample neighborhood for this study and is therefore selected as a representative neighborhood sample.

2.2. Micro-Meteorological Measurement

In this study, a total of 56 measurement points were positioned in a typical morphological area on the university grounds (Figures 1 and 2). The field study data comprised

two parts: the initial part involved measuring outdoor microclimate parameters using the HOBO weather station (Table 1), which included air temperature, relative humidity, solar radiation intensity and solar and wind velocity. The second part collected subjective evaluation data on thermal comfort through questionnaires, which included thermal sensation, preference and acceptance.

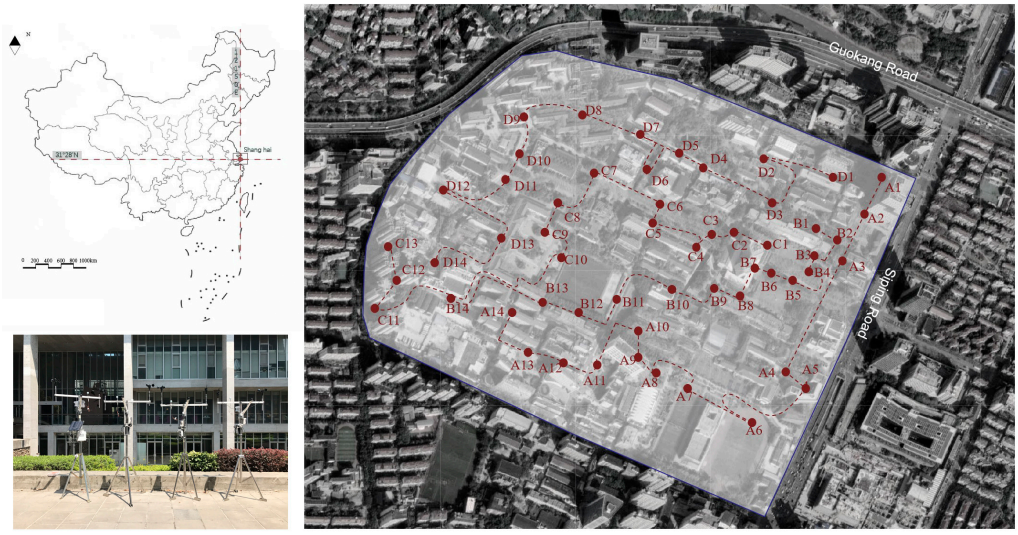


Figure 1. Map of measuring points and measured weather stations.



Figure 2. Point maps and fisheye camera photos.

Table 1. List of device parameters.

Device Model	Measurement Parameters	Accuracy Error	Range
H21-002 Micro weather station data logger	Recorded data	First data point 0 to 2 s at 25 °C (77 °F)	/
S-THB-M002 Temperature and humidity sensor	Air temperature/ relative humidity	Temperature: ±0.2 °C Humidity: ±2.5%	−40 °C to 75 °C 0 to 100%
S-LIB-M003 Total radiation sensor	Total solar radiation	±10 W/m^2 or ±5%	0 to 1280 W/m^2
S-WSET-B Wind speed and direction sensors	Wind speed/direction	±1.1 m/s	0 to 45 m/s
U23-001 Temperature and Humidity recorder	Air temperature/ relative humidity	Temperature: ±0.18 °C Humidity: ±2.5%	−40 to 75 °C; 0 to 100%
UX100-014M Temperature logger	Temperature	±0.6 °C	−26 to 950 °C

The impact of urban form on both environmental microclimate and human comfort is most notable in clear and windless conditions. Hence, tests were conducted on clear and

windless dates. The study was conducted over five days in spring—21, 26 and 27 March, 2 and 3 April—and three days in summer—17 June, 22 July and 17 September. The survey took place between 8:30 a.m. and 5:30 p.m. Each measurement point underwent testing for 15 min, with readings taken every 10 s, and the average of the 8–10 min of stable readings was used to obtain the meteorological parameters for this time period.

2.3. Questionnaire

The research questionnaire was divided into four parts: the first part was the demographics and research on the basic situation of the respondents; the second part was the subjective comfort evaluation such as thermal sensation and thermal preference votes, and thermal acceptance rate; the third part was the research on the activity level, space use and improvement measures of the respondents; and the fourth part was the clothing of the respondents. The second part of the questionnaire was the main part and the data collected by the questionnaire research were thermal sensation votes, thermal preference and thermal environment acceptance. The thermal sensation votes were based on the ASHRAE 7−degree standard, and the values taken from −3 to 3 are very cold (−3), cold (−2), colder (−1), moderate (0), hotter (1), hot (2) and very hot (3); the thermal preference votes were divided into three levels, namely wanting the environment to be colder (−1), unchanged (0) and hotter (1); and, the thermal acceptance votes were divided into two levels, namely acceptable and unacceptable. Respondents were also asked to describe their sensations and preferences for humidity, solar radiation and wind speed, where Humidity Sensation Votes (HSV) and Wind speed Sensation Votes (WSV) were divided into five rating levels, Radiation Sensation Votes (RSV) were divided into seven ratings and preference votes were divided into three ratings.

A total of 311 valid questionnaires were received in the spring; 357 valid questionnaires were collected during the summer fieldwork. The basic information of the respondents is shown in Table 2. The average length of time that the respondents have lived in Shanghai is 5.7 years, which indicates that the vast majority of the respondents have lived in Shanghai for some time and have adapted to the climatic and environmental conditions of the Shanghai area.

Table 2. Situation of respondents.

Spring Sample			Summer Sample		
Sample Size	**311**		**Sample Size**	**357**	
Sex	Male	184	Sex	Male	209
	Female	127		Female	148
Age	Average age	27.86	Age	Average age	24.82
	Standard deviation	12.29		Standard deviation	8.02
	Minimum value	6		Minimum value	5
	Maximum value	84		Maximum value	70

2.4. Thermal Comfort Indices

(1) Physiological Equivalent Temperature (PET)

The PET is a relatively physiologically based thermal model of the human body based on the MEMI [7]. The Physiological Equivalent Temperature is numerically equivalent to the air temperature of a standard human being in the measured environment when the body and skin temperatures reach the same values as in a standard indoor environment. The PET is one of the more important indicators used to evaluate outdoor thermal comfort, and there is a large body of literature using the PET as an assessment method [17], with a wide range of climatic regions of application.

In this study, the Rayman 1.2 software was used to calculate the physiological equivalent temperature. When the air temperature (Ta), relative humidity (RH) or vapor pressure (VP), wind velocity (WV), mean radiant temperature (Tmrt) or global radiation, and the

clothing and activity levels were given, Rayman was able to compute a specific value for the PET.

(2) Universal Thermal Climate Index (UTCI)

The UTCI is an index developed by the International Society for Biometeorology using the concept of equivalent temperature, based on the human thermal response model—the Fiala multimodal model and the thermal comfort model [18]. It is defined as the temperature at which the human body produces the same physiological response in the reference environment as in the actual environment (the activity level is equivalent to walking at 4 km/h and the environment is still, with a wind speed of 0.5 m/s and a distance of 10 m from the ground, which corresponds to a level of the human body of about 0.3 m/s, with no additional thermal radiation and 50% relative humidity and a vapor pressure not exceeding 20 hPa) [19]. This index simulates the dynamic physiological response using a model of human thermoregulation and a modern clothing model that does not depend on the characteristics of the person (age, sex, clothing, activity, etc.), and is one of the most commonly used metrics to evaluate the thermal state of a person in the outdoors [20]. In this research, the UTCI was calculated by the online version of the software (www.utci.org, accessed on 5 July 2022), where the numerical results of the UTCI be obtained by entering the temperature, relative humidity, wind speed and mean radiant temperature.

3. Results and Discussion

3.1. Thermal Environmental Level

The outdoor environmental parameters obtained from the HOBO weather station are presented in Table 3. Shanghai was characterized by a subtropical monsoon climate, which exhibited a moderately dry and temperate weather pattern during the spring season. The recorded air temperature during the spring testing period ranged from 15.0 to 23.4 °C, with an average temperature of 19.4 °C and an average humidity level of 28.71%. The wind speed during the test was still conducted in calm breeze weather, with an average wind speed of 0.83 m/s, and it exhibited significant variation as a result of obstruction caused by trees and buildings, resulting in an average solar radiation intensity of 414.25 W/m^2. The outdoor environment of the campus during the summer exhibits characteristics commonly found in hot and humid climates. The average relative humidity was 49.99%, with air temperature ranging from 24.1 to 39.6 °C, and an average temperature of 30.70 °C. The wind speed was relatively low, with an average wind speed of only 0.47 m/s, which is significantly below the threshold of 1.0 m/s. This was attributed to the experimental design, which intentionally selected static wind conditions for the weather. Because some of the measuring points were on campus, certain measuring points were positioned to the north of high-rise buildings, resulting in variations in radiation intensity.

Table 3. Outdoor environmental meteorological parameters.

	Spring				Summer			
	Minimum	**Maximum**	**Average**	**Standard Deviation**	**Minimum**	**Maximum**	**Average**	**Standard Deviation**
Air temperature °C	14.99	23.40	19.40	2.12	24.08	39.63	30.70	4.20
Relative humidity %	17.01	43.10	28.71	7.20	30.74	67.81	49.99	8.57
Globe temperature °C	16.41	28.51	22.20	2.95	24.39	44.84	32.47	4.64
Solar radiation w/m^2	28.33	930.08	414.25	271.63	5.00	956.53	318.93	296.02
Wind speed m/s	0.03	2.73	0.83	0.57	0.00	2.73	0.47	0.51
Mean radiation temperature °C	17.05	42.08	26.94	6.02	29.13	49.30	34.42	5.67
PET °C	11.30	39.30	24.17	6.595	22.10	56.60	35.44	8.55
UTCI °C	13.27	25.60	20.07	2.806	22.99	43.62	31.22	4.64

3.2. Thermal Comfort Status

3.2.1. Subjective Thermal Reaction Votes

The subjective comfort analysis was based on data collected from 311 valid spring questionnaires and 357 summer questionnaires, with the survey time evenly distributed between 8.30am and 5.30pm on sunny days.

(1) Thermal sensation votes (TSVs) and thermal preference votes (TPVs)

TSVs were derived from the ASHRAE 7−degree standard, taking values from −3 to 3 as very cold (−3), cold (−2), colder (−1), moderate (0), hotter (1), hot (2) and very hot (3); and TPVs were divided into three levels as wanting the environment to be colder (−1), unchanged (0) and hotter (1). The average temperature during the spring implementation period was 19.4 °C (Table 3) and the votes results are shown in Figure 3. The findings of the TPVs and TSVs were not identical, as a greater proportion of participants (26%) perceived the temperature to be on the hot side (TSV > 0), while a higher percentage of respondents (24%) expressed a desire for a hotter environment (TPV > 0). This may be due to the fact that in the early spring season, the air temperature during the test period ranged from 15 to 23.4 °C, the temperature difference between the nighttime and daytime in Shanghai was large, the average temperature was low and the test time was during the day, especially in the period close to midday. People would feel that the ambient temperature was moderate or on the hot side according to the dress code in the morning and evening when they were out of the office, but in terms of the all-day climatic environment, peoples' psychological expectation was that the outdoor environment would be on the warmer side. This view can be supported by the fact that of the 202 respondents who perceived the ambient temperature as moderate (TSV = 0), 47 (23%) wanted it to be hotter (TPV = 1) and only 12 (6%) wanted it to be colder (TPV = −1). During the summer months, TSVs and TPVs were basically the same.

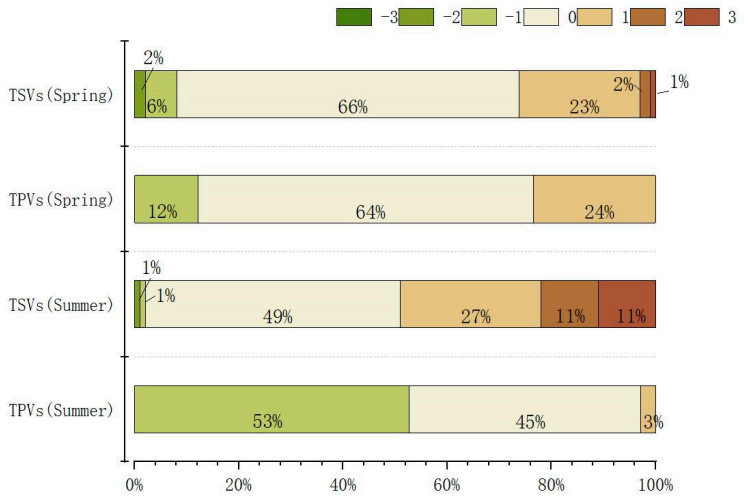


Figure 3. Thermal sensation votes and thermal preference votes.

(2) Humidity sensation votes (HSVs) and humidity preference votes (HPVs)

The humidity sensation votes (HSVs) were categorized into five levels, namely very dry (−2), dry (−1), moderate (0), humid (1) and very humid (2). The humidity preference vote (HPV) is divided into three levels: wanting the environment to be drier (−1), unchanged (0) and more humid (1). The relative humidity during the spring research period ranged from 17% to 43%, with an average relative humidity of 28.7%, as shown in Figure 4, and the HSV and HPV results were basically in agreement. According to the respondents' feedback, the humidity during the test period was moderately slightly dry for people.

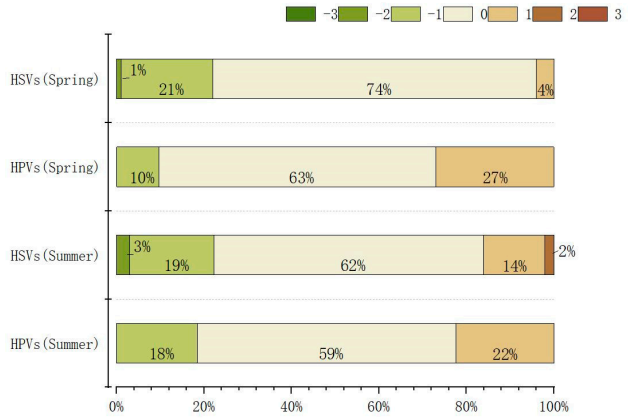


Figure 4. Humidity sensation votes and humidity preference votes.

The relative humidity during the summer testing period ranged from 30.7 to 67.8%, with an average humidity of about 50%. From the statistical results of the meteorological parameters of the environment in which the respondents were located during the previous research period, it could be seen that the relative humidity was 49.99%, which was a relatively moderate range of humidity. This finding was also consistent with the results of the humidity sensation votes and the humidity preference votes.

(3) Wind speed sensation votes (WSVs) and wind speed preference votes (WPVs)

WSVs were divided into five levels, namely no wind (−2), less wind (−1), moderate (0), more wind (1) and too much wind (2); and WPVs were divided into three levels, namely wanting the environment to be even less windy (−1), unchanged (0) and more windy (1). Most of the test periods were chosen to be lightly windy days, and the average wind speed during the spring test period was 0.8 m/s. The statistical results (Figure 5) show that the rate of respondents who wanted the wind speed to remain unchanged (WPV = 0) (61%) was significantly higher than the number of respondents who thought the wind speed was moderate (WSV = 0) (35%). Additionally, the number of respondents who thought the wind speed was too low (WSV < 0) (40%) was significantly higher than the number of respondents who thought the wind speed was higher (2) (WPV = 1) and the number of respondents who thought the wind speed was too high (1) (WPV = 1) (11%), suggesting a preference for low wind speed environments in early spring, when air temperatures were still low. Moreover, this result also proves that wind speed sensation votes (WSVs) and wind speed preference votes (WPVs) sometimes do not coincide.

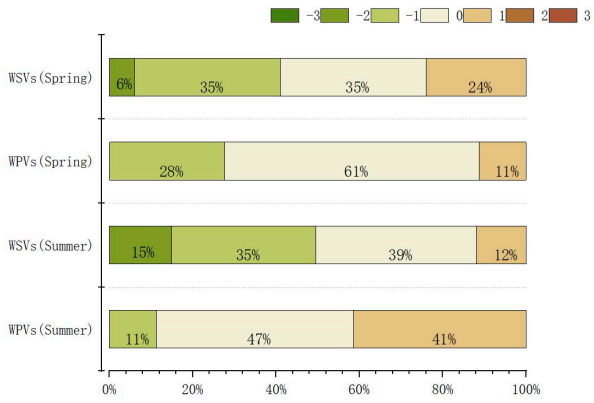


Figure 5. Wind speed sensation votes and wind speed preference votes.

The average wind speed during the summer testing phase was 0.83 m/s. The statistical results of the data show that the WSV results were basically in line with the WPV results; 11% of the respondents expressed a preference for a lower wind speed, while 47% would

like to have no change in the wind speed. Conversely, 41% of the respondents expressed a desire for a higher wind speed. According to the statistical analysis of the meteorological parameters, it could be seen that the average wind speed of the environment where the respondents were located during the field research was recorded as 0.47 m/s, and people expected higher wind speed to achieve the expectation of cooling. Therefore, enhancing the ventilation effect by implementing rational and efficient measures is an effective approach to enhancing outdoor comfort during the summer season.

(4) Radiation sensation votes (RPVs) and radiation preference votes (RPVs)

RSVs were divided into seven levels of very weak (−3), weak (−2), weak (−1), moderate (0), strong (1), strong (2) and very strong (3); RPVs were divided into three levels of wanting the intensity of solar radiation to be weaker (−1), unchanged (0) and stronger (1). The average solar radiation intensity during the spring test period was 414.3 w/m^2, as shown in Figure 6. The statistical results of RSVs and solar radiation feeling preference were basically the same. However 49% of the respondents thought that the solar radiation was moderate (RSV = 0), but 60% of them wanted the radiation intensity to remain unchanged, and 34% of the respondents think that the solar radiation was strong (RSV > 0), but only 25% of the respondents want the solar radiation to be weaker (RPV = −1). This was because of the 107 respondents who felt that the solar radiation was strong (RSV > 0), 39 or 36% of the respondents wanted it to remain the same (RPV = 0), so it can be seen that the respondents had a preference for more sunshine in climates with cooler spring temperatures.

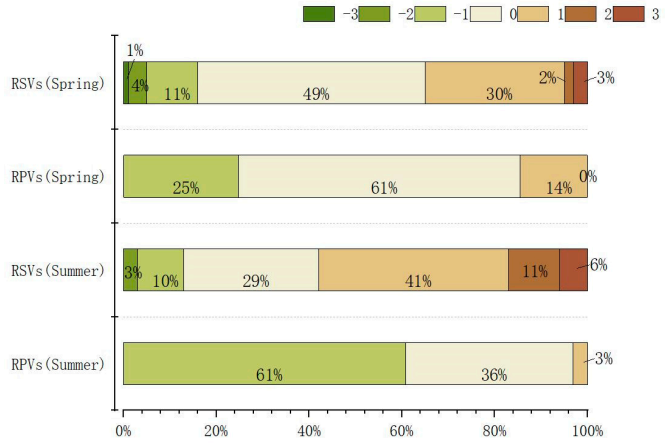


Figure 6. Radiation sensation votes and radiation preference votes.

The average solar radiation recorded during the summer test period was 318.9 W/m^2. However, it is important to note that the intensity of solar radiation exhibited significant variation across different measurement points. This variation can be attributed to the presence of shading caused by buildings or vegetation at approximately most measurement points. The results of HSVs and HPVs are slightly different, with only 3% of respondents wanting the sunshine intensity of their environment to increase, 61% wanting it to decrease and 36% wanting it to remain the same. This suggested that during the summer months, when air temperatures are high, respondents' psychological expectations are more in favor of less solar radiation.

3.2.2. Correlation between Subjective Feeling Votes

From the previous statistics, it can be seen that the distributions of TSVs, HSVs, WSVs and RSVs all show some tendency and do not follow the normal distribution. Table 4 analyses the relationships between TSVs, HSVs, WSVs and RSVs in spring and summer, respectively, using correlation analysis.

Table 4. Comfort sensation votes correlation analysis in spring and summer.

			HSVs	WSVs	RSVs
Spring	TSV	Pearson correlation	−0.025	−0.218 **	0.367 **
		Significance (two-sided)	0.661	0.000	0.000
		N	311	311	311
Summer	TSV	Pearson correlation	−0.067	−0.488 **	0.477 **
		Significance (two-sided)	0.209	0.000	0.000
		N	357	357	357

The cells contain zero-order (Pearson) correlations. ** Correction is significant at the 0.01 level (two-tailed).

Through the correlation analysis of the comfort votes in spring and summer, it can be seen that there is a significant positive correlation between TSVs and RSVs, and TSVs and WSVs, which are both parameters with a two-sided significance of 0.00; there is a significant negative correlation between TSVs and WSVs in spring and summer. Based on the above correlation analyses, we can conclude that solar radiation and wind speed are important outdoor environmental parameters that affect human outdoor thermal comfort in spring and summer. Therefore, by reasonably installing vegetation and shading devices to block the strong solar radiation, and directing the outdoor ventilation to create a comfortable wind environment, the human outdoor thermal comfort in summer can be improved in this area.

3.3. Outdoor Thermal Comfort Specificity Analysis

3.3.1. Analysis of the Applicability of PET to UTCI

In order to establish the correlation between the thermal sensation votes and the thermal comfort of people at different (PET, UTCI) values, the spring–summer comfort index (PET, UTCI) was divided into multiple temperature segments, each with a 0.5 °C interval. Subsequently, the mean thermal sensation votes (MTSVs) were calculated for each segment.

This was carried out to try to eliminate the randomness of a small sample. Binary regression analyses were performed with mean thermal sensation votes as the dependent variable and the PET and UTCI as the independent variables, respectively, to obtain the regression equations for the PET, UTCI, and MTSVs, and it was found that there was a significant linear relationship between MTSVs and each comfort index. The correlation equation between the MTSVs and PET is shown in Table 5.

Table 5. Linear regression equation in spring and summer.

Thermal Comfort Indices	Season	Linear Regression Equation	R^2
PET	spring	MTSVs = 0.0585PET − 1.3043	R^2 = 0.5576
	summer	MTSVs = 0.0702PET − 1.7234	R^2 = 0.7616
UTCI	spring	MTSVs = 0.1274UTCI − 2.3893	R^2 = 0.7770
	summer	MTSVs = 0.1599UTCI − 4.1992	R^2 = 0.8255

The slopes of MTSVs with PET values in spring and summer were 0.0585 and 0.0702, respectively, as depicted in Figure 7 (left). This indicates that the sensitivity of MTSVs to the PET varied slightly between the two seasons. In spring, the PET can cause a change of one unit of mean thermal sensation votes (MTSVs) every 17.1 °C, and in summer, the PET can cause a change of one unit of MTSVs every 14.2 °C. These findings suggest that individuals exhibit greater adaptability to environmental comfort in spring, are less sensitive to PET changes during this season, and are more sensitive to PET changes in summer. The slopes of MTSVs with UTCI curves in spring and summer were 0.1274 and 0.1599 as shown in Figure 7 (right). In comparison to the PET, the MTSVs slopes exhibited minimal changes with respect to UTCI variations during the spring and summer seasons. Specifically, every

7.8 °C of the UTCI in spring caused one unit of MTSVs change, and every 6.25 °C of the UTCI in summer caused one unit of MTSVs change.

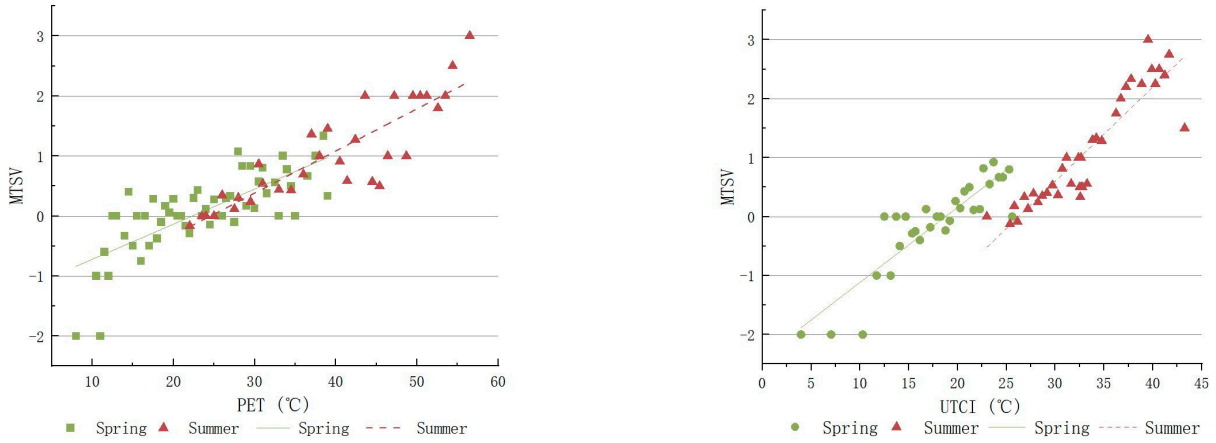


Figure 7. Relationship between TSVs and PET in spring and summer (**left**) Relationship between TSVs and UTCI in spring and summer (**right**).

In addition, Table 5 and Figure 7 show that the R^2 of the PET and UTCI in the spring and summer were both greater than 0.6, indicating that both comfort indicators were able to reflect the thermal sensation of people in the Shanghai region during these seasons, similarly to the results of another study conducted in the Shanghai area [11]. The study shows that during the spring seasons, the correlation between the UTCI and mean thermal sensation was higher, with an R^2 of 0.777, which means that the UTCI can better characterize the thermal sensation of people in spring. During the summer seasons, the correlation between TSVs with UTCI or PET, was 0.69 and 0.78 respectively, the difference was not so much. In summer, the correlation between the UTCI and TSVs were slightly higher than that of the PET. Therefore, from the results of the analyses conducted during the spring and summer seasons, it can be concluded that there is a stronger correlation between the UTCI and the TSVs in Shanghai. This correlation was deemed more suitable for assessing the perception of heat in Shanghai.

3.3.2. Neutral Temperature and Heat Sensitivity

The outdoor neutral temperature reflects the requirements for human thermal comfort in outdoor spaces. The neutral temperature was commonly defined as the thermal comfort environment that was deemed acceptable by the majority of individuals. In this research, from the linear equations of MTSVs and each comfort level, it could be deduced that the neutral PET in Shanghai was 22.30 °C and 24.55 °C in spring and summer; and the neutral UTCI was 18.75 °C and 26.26 °C in spring and summer, (Table 6). The neutral PET varies between seasons. In this study, the neutral PET was 2.25 °C higher in summer than in spring, and the neutral UTCI was 7.51 °C higher in summer than in spring, suggesting that seasonal changes have a significant effect on thermal comfort. Similar results were found by Li [21] et al.

Table 6. Neutral temperature and thermal comfort range for thermal comfort indicators in spring and summer.

Thermal Comfort Indices	Season	Neutral Temperature	90% Acceptance Range	Two Seasons 90% Acceptance Range
PET	spring summer	22.30 °C 24.55 °C	20.5~31.4 °C <20.4 °C	25.0~32.1 °C
UTCI	spring summer	18.75 °C 26.26 °C	18.3~25.3 °C <23.3 °C	24.2~27.7 °C

From the analysis presented in Table 7, it was apparent that the results obtained from Singapore, Harbin (China), and Tianjin (China), which are all located in the northern hemisphere, are consistent with the findings of this study. Specifically, as the seasons progress, the neutral PET was observed to be higher in summer compared to winter. However, the conclusions drawn for Damascus, Syria and Sydney, Australia, in the southern Hemisphere, were contrary to this pattern, as the neutral PET is higher in winter than in summer as the seasons advance. Furthermore, it was important to note that neutral temperatures exhibited variations across different climate zones. The summer neutral temperature in Glasgow, United Kingdom, with an oceanic climate, was 13.5 °C; the summer neutral temperature in Shanghai, China, with a temperate monsoon climate, was 24.5 °C; and the summer neutral temperature in Cairo, Egypt, with a desert climate, was 30.1 °C. The outdoor neutral PET was higher in cities with hot climates than in cities with cold climates.

Table 7. Comparison of other outdoor thermal comfort studies.

Climatic Zone	City	Neutral PET	Neutral UTCI
Arid climate region	Cairo (Egypt) [22]	30.1 °C Hot month 29 °C Cold month	/
Temperate marine climate	Glasgow (UK) [23]	13.5 °C summer	/
Tropical Mediterranean climate	Damascus (Syria) [24]	15.7 °C summer 24.2 °C winter	/
Mediterranean climate	Sydney (Australia) [25]	22.9 °C summer 28.8 °C winter	/
Tropical monsoon climate	Singapore [6]	28.7 °C summer	23.5 °C summer
Subtropical monsoon climate	Shanghai (This study)	22.30 °C spring 24.55 °C summer	18.75 °C spring 26.26 °C summer
	Changsha (China) [26]	27.9 °C summer	/
	Hong Kong (China) [27,28]	25 °C summer 21 °C winter	22.7 °C summer
Temperate monsoon climate	Harbin (China) [29]	20.0 °C summer 13.2 °C winter	/
	Tianjin (China) [10]	15.55 °C summer	17.5 °C annual
	Xi'an (China) [30]	23.27 °C summer	23.1 °C Winter and summer average

3.3.3. 90% Acceptance Range

In order to obtain the thermal acceptability situation of the PET and UTCI, a mathematical model was developed between the unacceptability rate votes (URVs) and the two comfort indexes, using the same methodology as for the calculation of thermal sensation votes. The thermal unacceptability rate was defined as the percentage of thermal unacceptability votes out of the total votes. In this paper, the unacceptability rate votes were grouped by 1 °C PET or UTCI and the percentage of thermal unacceptability votes in each group of samples was calculated. To avoid the grouping of data with small sample sizes affecting the accuracy of the analysis results, data groups with sample sizes less than 5 were removed from the analysis and each group of thermal unacceptability rate and their PET/UTCI were fitted, analyzed and obtained, as shown in Table 8.

Table 8. Relationship of the thermal unacceptability rate of the residents and the comfort index in different season.

Thermal Comfort Indices	Season	Equation	R^2
PET	spring	$URV = 0.3PET^2 - 15.59PET + 203.56$	$R^2 = 0.6719$
	summer	$URV = 148PET - 301.6$	$R^2 = 0.5196$
	two seasons	$URV = 0.13PET^2 - 7.44PET + 114.83$	$R^2 = 0.5349$
UTCI	spring	$URV = 0.57UTCI^2 - 248.9UTCI + 274.6$	$R^2 = 0.7897$
	summer	$URV = 2.92UTCI - 67.97$	$R^2 = 0.7849$
	two seasons	$URV = 0.22UTCI^2 - 11.42UTCI + 157.54$	$R^2 = 0.6587$

As shown in Figure 8, the rate of unacceptability in the spring season exhibited a quadratic relationship with the value of PET. The acceptance rate of the thermal environment reached the maximum value when the value of PET was 26.0 °C, and subsequently decreased as the environment became either warmer or colder. In contrast, the rate of unacceptability in the summer season showed a linear correlation with the PET, and the acceptance rate of the thermal environment increased with higher values of the PET. In the spring season, the relationship between the thermal unacceptability rate and the UTCI followed a quadratic function. The thermal environment acceptance rate reached its maximum value when the UTCI value was 21.8 °C. On the other hand, during the summer season, there was a linear relationship between the thermal unacceptability rate and the UTCI. The thermal environment unacceptability rate increased gradually with the increase in the UTTCI.

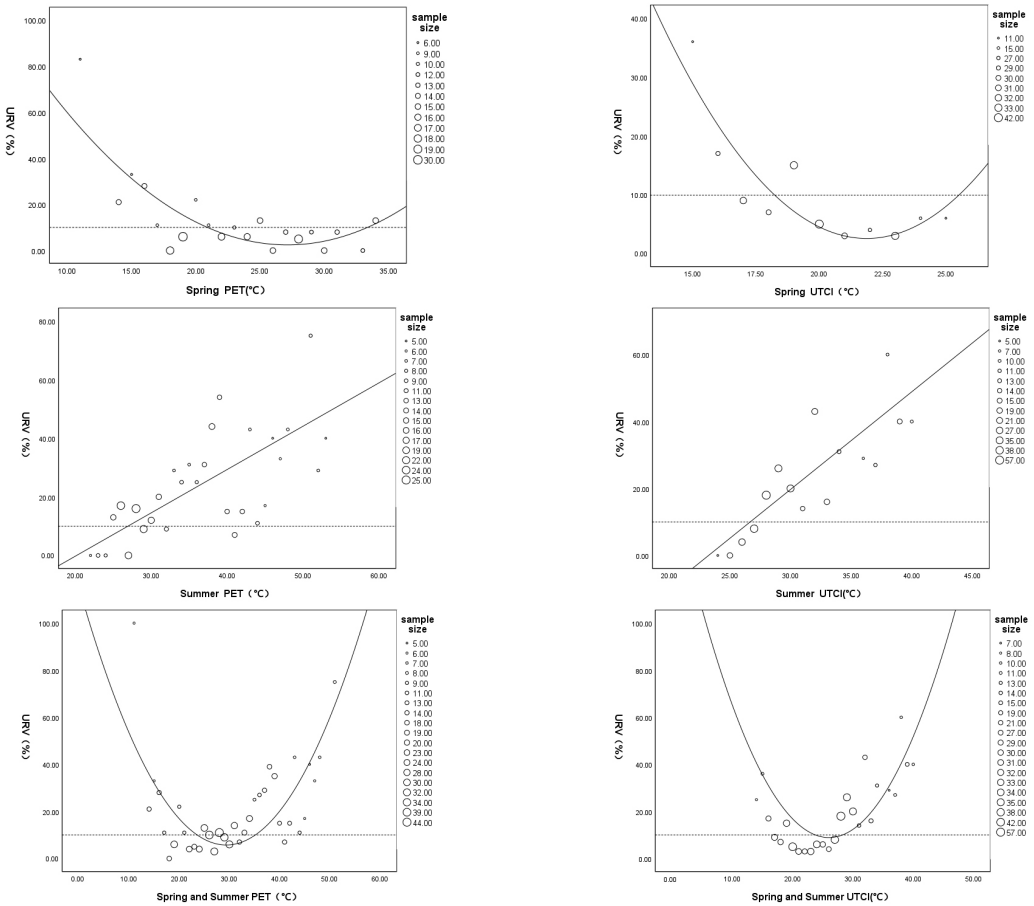


Figure 8. Correlation of URVs with comfort indicators.

According to ASHRAE Standard 55, the thermal environment was considered satisfactory when the acceptability of the outdoor thermal conditions reached 90%. After conducting the data processing and calculations for the spring and summer seasons in Shanghai (Figure 8), it had been determined that the 90% acceptable range for the PET is 25.0~32.1 °C, whereas the UTCI range was 24.2~27.7 °C. From the analysis presented in Table 9, it was apparent that the acceptable ranges of values demonstrated variations among various climate zones. Due to the prevailing hot climate and significant temperature fluctuations between morning and evening, the acceptable range of temperature in Haryana, India, characterized by a semi-dry monsoon climate, was 24.04~37.55 °C, which was relatively wider. However, due to the cooler year-round temperatures, Glasgow, United Kingdom, which had an oceanic climate, had a lower acceptable PET range in the winter to summer (three-season) period (9 to 18 °C), and residents were more tolerant of the lower climate. Shanghai and Changsha [26], two cities in China, exhibit a similar subtropical monsoon climate. The 90% acceptable PET range in Changsha is wider than in Shanghai. The reason for Changsha being hotter in the summer can be attributed to the topography of the city. The local inhabitants are accustomed to the high temperatures in the region. People have the capacity to modify their ability to acclimate and endure extreme temperatures in response to alterations in their surroundings. According to Humphreys et al., respondents may be inclined to adjust their votes to the various conditions they experience.

Table 9. Comparison of 90% acceptable range in different areas.

Climatic Zone	City	90% Acceptance Range
Arid climate region	Cairo (Egypt) [31]	24.3~29.5 °C (PET) Winter and summer
Marine climate	Glasgow (UK) [23]	9~18 °C (PET) Three seasons
Semi-dry monsoon climate	Haryana (India) [32]	24.04~37.55 °C (PET) summer 28.03~35.6 °C (UTCI) summer
Temperate continental climate	Umea (Sweden) [16]	10–17 °C (PET) summer 11.5~17.2 °C (UTCI) summer
Temperate monsoon climate	Harbin (China) [29]	11.6~35.9 °C (PET) summer
	Tianjin (China) [10]	11~24 °C (PET) annual 13.6~21.3 °C (UTCI) annual
Subtropical monsoon climate	Shanghai (This study)	25.0~32.1 °C (PET) Spring and summer 24.2~27.7 °C (UTCI) Spring and summer
	Changsha (China) [26]	18.6~31.2 °C (PET) summer
Tropical monsoon climate	Singapore [26]	18.7~30.3 °C (PET) summer

3.4. Dress Code and Thermal Adaptation Behavior

3.4.1. Clothing Thermal Resistance

According to ASHRAE Standard 55 and ISO Standard 7730 (ASHRAE, 2020; ISO 7730, 2005), clothing insulation values and metabolic rates were based on the respondents' clothing type and activity level. This allowed for the calculation of a single clothing thermal resistance, which was obtained using the following Equation (1). Additionally, when considering clothing habits, women should add 0.05 clo to the obtained clothing thermal resistance.

$$I_{CL} = 0.835 \sum I_{clu,i} + 0.181 \quad (1)$$

In the equation, I_{CL} is the combined garment thermal resistance; $I_{clu,i}$ represents the single garment thermal resistance

The findings indicated that during the spring season, the average thermal resistance was measured at 0.788 clo, while during the summer season, it was recorded at 0.434 clo. It was observed that individuals adjust their clothing in response to temperature changes, either by adding or removing layers. Furthermore, it was noted that females exhibited a

higher average thermal resistance compared to males in both seasons. This phenomenon could be attributed to the fact that women generally have a higher body fat index and lower skin temperature compared to men [33]. Similarly, the range and insulation of women's clothing typically surpassed that of men's [34] (Figure 9).

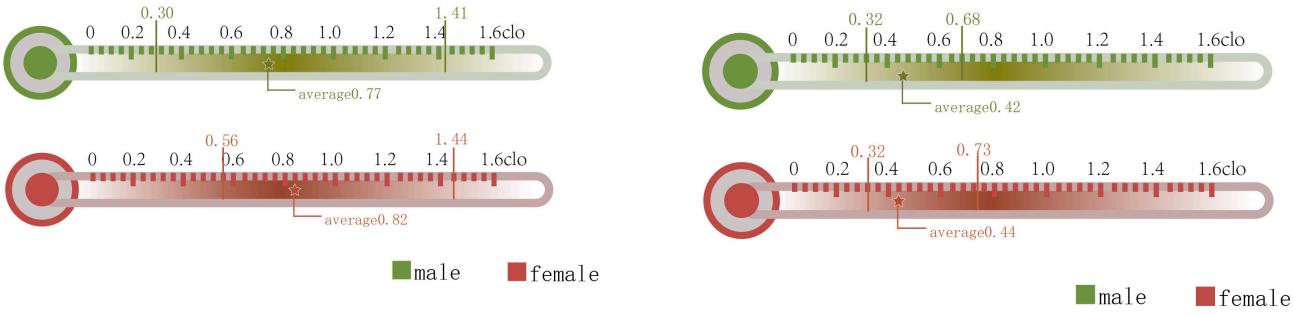


Figure 9. Thermal resistance of clothing for spring crowds (**left**) Thermal resistance of clothing for summer crowds (**right**).

3.4.2. Thermal Adaptive Behavior

The results of the research showed that in spring, more respondents (24%) would like the temperature to be hotter. In terms of cold adaptation behavior, 38.8% of respondents would prefer to go to a sunny place to sunbathe, 21.6% of respondents would choose to wear more clothes and relatively fewer respondents would choose to go to a place sheltered from the wind (17.5%) and drink hot drinks (12.7%) (Figure 10, left).

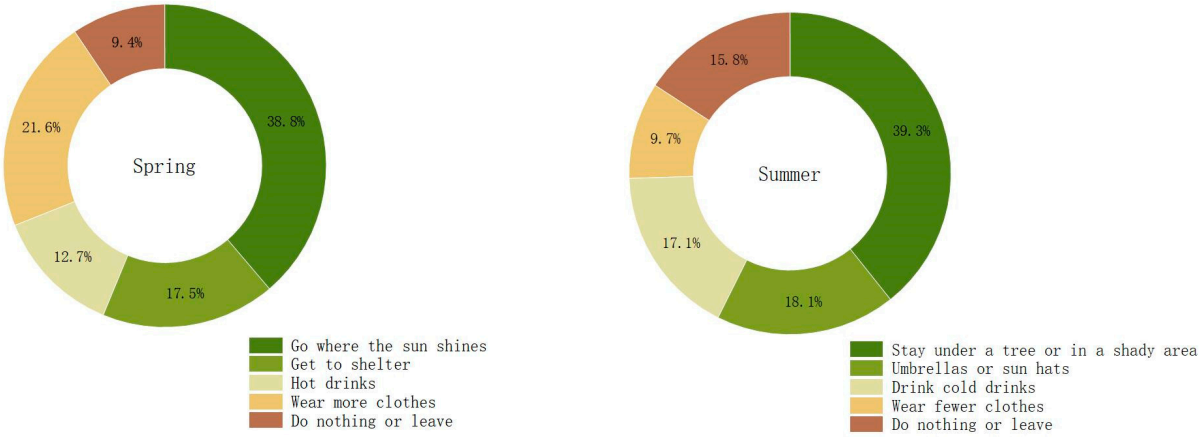


Figure 10. Spring cold adaptation behavior; (**left**) summer heat adaptation behavior (**right**).

In summer, the majority of respondents (53%) would like the temperature to be colder. In terms of heat adaptation behavior, more respondents (39.2%) would choose to stay under a tree or in a shady place, followed by using an umbrella and sun hat (18.1%) or drinking cold drinks (17.1%), and relatively fewer would choose to wear less clothing (9.7%). The findings from the spring and summer surveys indicated that, apart from modifying shading devices and adjusting the amount of clothing worn, measures such as adjusting planting, building shading, paving and implementing controlled ventilation are crucial methods for enhancing the thermal conditions in outdoor areas (Figure 10 right).

4. Conclusions

Through the measurement of environmental parameters and questionnaire research conducted in typical urban areas of Shanghai during warm seasons, this study comparatively analyzed the applicability of the comfort index in different seasons in Shanghai. Based on the findings, the following conclusions were drawn:

(1) The analysis of correlation between the thermal sensation votes and the microclimate parameters showed that there is a negative correlation between TSVs and WSVs, as well as a positive correlation with RSVs during spring and summer. However, there is no significant correlation between RSVs and WSVs and HSVs in spring. It can be inferred that solar radiation and wind speed were most significant outdoor environmental factors that influence human outdoor thermal comfort during summer.

(2) In the hot summer and cold winter region represented by Shanghai, the neutral PET was 22.30 °C and 24.55 °C in spring and summer, respectively; the neutral UTCI was 18.75 °C and 26.26 °C in spring and summer, respectively. The range of 90% acceptable PET in Shanghai is 25.0–32.1 °C and the range of the UTCI is 24.2–27.7 °C. This study evaluated the effectiveness of two thermal indices, the PET and UTCI. Compared with the two thermal indices, it was observed that the correlation between the UTCI and the average thermal sensation votes was higher. This indicates that the UTCI is more effective in characterizing the thermal sensation experienced by people in Shanghai.

(3) During the research period, evidence of thermal adaptation was observed. The average thermal resistance values were determined to be 0.788 clo during the spring season and 0.434 clo during the summer season. A negative correlation was observed between the average clothing insulation and temperature. It was observed that people adapts to the temperature changes by modifying their clothing, either by adding or removing layers. Interestingly, hat females demonstrated a higher average thermal resistance in comparison to males during warm seasons.

These conclusions can provide a basis for the evaluation of environmental thermal comfort and the practical optimization path for climate-responsive urban design in high-density urban areas.

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