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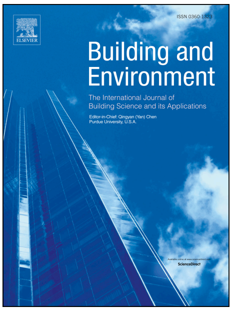

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Outdoor thermal comfort and adaptive behaviors in a university campus in China’s hot summer-cold winter climate region

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Abstract: Outdoor thermal comfort in the university campus is an important issue for encouraging students’ outdoor activities and interactions. This research conducted field measurement and questionnaire survey in a university campus in Mianyang, located in the hot summer and cold winter climate zone according to China’s climate classification for building design and the dry-winter subtropical climate according to the Köppen climate classification. The measurements were conducted over six days in winter and four days in summer; meanwhile, the survey collected 523 responses. Respondents preferred "slightly warm" in winter and "slightly cool" in summer. The range of 90% acceptable PET (Physiologically Equivalent Temperature) was higher than 20.2 °C in winter, lower than 35.6 °C in summer, and between 20.5 °C and 35.7 °C in a year. When PET increased by one degree Celsius, the probability of "using umbrella", "taking off clothes" and "going to a shaded place" increased by 22.6%, 4.9% and 16.6%, respectively; while the probability of "staying under the sun" decreased by 17.5%. Neutral temperatures in different seasons were examined and compared with those from other studies. These findings provide evidence for planning and design strategies to improve the thermal environment of outdoor spaces.

Keywords: Campus outdoor space; hot summer-cold winter climate region; thermal comfort; adaptive behaviors; planning and design

1. Introduction

In recent years, thermal comfort has come to the research spotlight due to the increasing attention to both energy efficiency and human wellbeing [1]. In ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards, thermal comfort is defined as the degree of subjective satisfaction of human with the thermal environment [2]. Depending on the location, thermal comfort can be categorized into indoor thermal comfort, semi-outdoor thermal comfort and outdoor thermal comfort. To date, most research focused on the indoor space where thermal environments are relatively stable; the research of thermal comfort in outdoor non-steady state environments was comparably insufficient. There are more and more voices advocating outdoor activities for better health outcomes [3]. University students spend most of their time in front of computers, it is thus crucial to encourage them to engage with outdoor activities for our next generation’s health and wellbeing. There is an urgent call for more research on thermal comfort in campus outdoor environments.

There are many research efforts in the outdoor thermal comfort field. These studies were conducted in urban streets, squares and parks [4-6] and across different climates, such as Mediterranean climate [7, 8], hot desert climate [9], subtropical climate [10], tropical climate [11] and continental climate [12, 13]. These studies used different comfort indices, such as PET (Physiologically Equivalent Temperature) [9], SET* (Standard Effective Temperature) [14], operative temperature [11] and UTCI (Universal Thermal Climate Index) [10]. These studies reveal that outdoor microclimate does have an important impact on human thermal comfort and utilization of outdoor spaces.

Thermal comfort studies focusing on campus facilities have been conducted both indoors and outdoors. For example, Liu et al. [15] investigated the students' thermal comfort in natural ventilated university classrooms during cold days in the temperate climate and found that the thermal neutral temperature was 20.6 °C with the comfort temperature ranging from 19.5 to 21.8 °C. The studies have also investigated thermal comfort in office facilities in the campus [16, 17]. For campus outdoor areas, Huang et al. [18] compared thermal comfort in the semi-outdoor area and in the outdoor open area in a university campus of Hong Kong with a subtropical climate. The results showed that the neutral PET for the semi-outdoor area was 21.0 °C and 22.7 °C for the outdoor open area. Zhao et al. [14] showed that the neutral SET* index was 23.9 °C in the outdoor area of Guangzhou in a subtropical zone. The result was similar to that of Xi et al. [19] who conducted outdoor thermal comfort in campus outdoor spaces in the same climate zone. Fewer studies have been conducted in China's hot summer-cold winter climate regions where outdoor weather is opposite in winter and summer and people in this climatic region have developed strong thermal adaptability [20]. Studies in outdoor thermal environment in this region can help explore ways to create a comfortable outdoor thermal environment based on local practice.

In this research, the campus of Southwest University of Science and Technology, located in Mianyang, China, was selected for the study. Based on the average temperature of the coldest month (January) and the hottest month (July), China's national climate classification identifies five major climatic zones for building design (Figure 1). Mianyang is in the hot summer and cold winter climate region. In this region, the average temperature of the coldest month is between 0 and 10 °C, and the average temperature of the hottest month is between 25 and 30 °C; the number of days with the daily average temperature lower than 5 °C is between 0 and 90, and the number of days with the daily average temperature higher than 25 °C is between 49 and 110 [21].

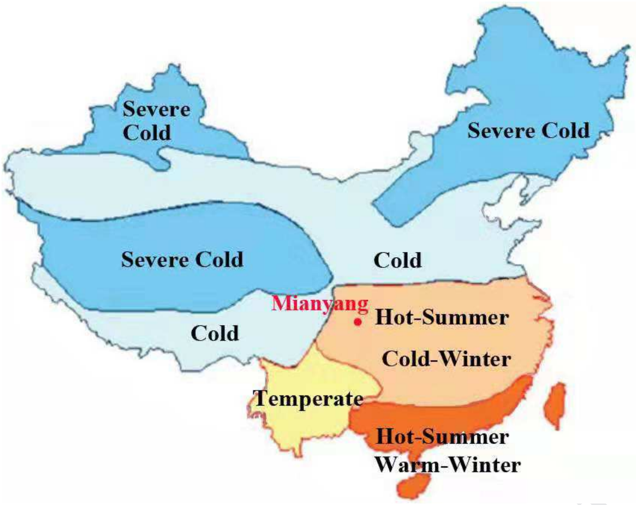

Fig.1. The climate classification for building design in China and the location of Mianyang city (Source: [21])

Mianyang has not been investigated for thermal comfort, probably due to its relatively isolated location and underdeveloped economy. The purpose of this research is to understand the thermal comfort in the campus outdoor space in Mianyang, including its comfort temperature, acceptable temperature range, students' adaptive behaviors, based on which practical campus planning and design strategies could be proposed. The main objectives of this study are:

1). To investigate the thermal perceptions of people in a university campus of Mianyang, and compare the results with previous outdoor thermal comfort studies.

2). To test the effects of shading and biological sex on outdoor thermal comfort.

3). To investigate participants' different adaptive behaviors to achieve thermal comfort in outdoor space.

2. Methodology

2.1 The campus

The campus of Southwest University of Science and Technology (104.73°E, 31.48°N) is located in Northeast Mianyang City, Sichuan Province in China. According to the local meteorological records (Figure 2), the monthly outdoor air temperature varies from 3.5 °C to 31.0 °C in a year, with the highest monthly mean temperature in July (26.6 °C) and August (26.1 °C), and the lowest monthly mean temperature in January (6 °C) and December (7.5 °C). Relative humidity has little variation throughout the year, ranging between 64% and 78%.

Figure 3 shows the variation of daily mean maximum temperature, minimum temperature and mean temperature of a typical year in Mianyang. According to the division of seasons with pentad mean temperature method used in the meteorological industry standard - Climatic Seasonal Division [22], the first day with pentad mean temperature less than 10 °C is defined as the beginning of winter, and the first day with pentad mean temperature greater than 22 °C is defined as the beginning of summer. The period with the pentad mean temperature between 10 °C and 22 °C is considered as spring or autumn. By this method, it can be seen that the summer in Mianyang lasts from the beginning of May to the end of September for five months, the winter lasts from the beginning of December to the end of February of the following year for three months, while the spring and autumn last for relatively short durations, from March to April and October to November respectively. Two extreme and longer seasons—summer and winter are selected for the outdoor thermal comfort and adaptive behaviors study.

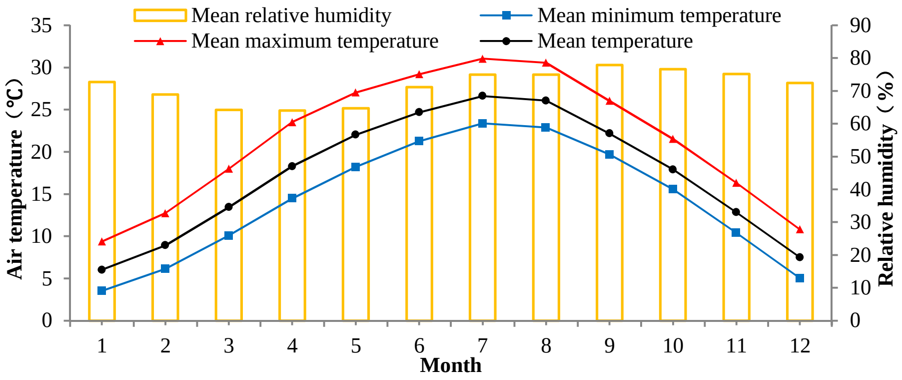

Fig.2. The monthly variation of temperature and relative humidity in Mianyang (2000–2017).

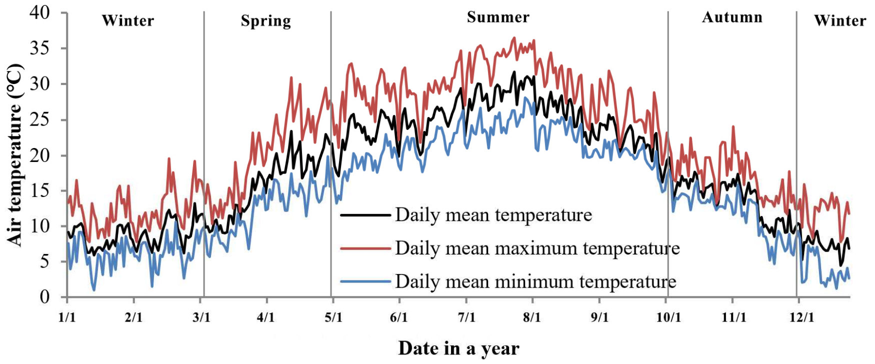

Fig.3. The daily temperature variation in a typical year in Mianyang.

The spots for measurement are shown in Figure 4. Southwest University of Science and Technology is divided into lower and upper campuses. Four spots representative of the crowd activities were selected in each campus for data collection. Spots 1-4 in the lower campus are located in the green space next to new campus library, the green space in the central lake, the stadium in new campus and the "power of science" square, respectively; Spots 5-8 in the upper campus are located in the small square next to the old campus library, the willow pool, the Longshan Stadium and the material square, respectively. Spot 1 and 5 are under trees’ canopies, representing shaded places while other points are in open spaces.

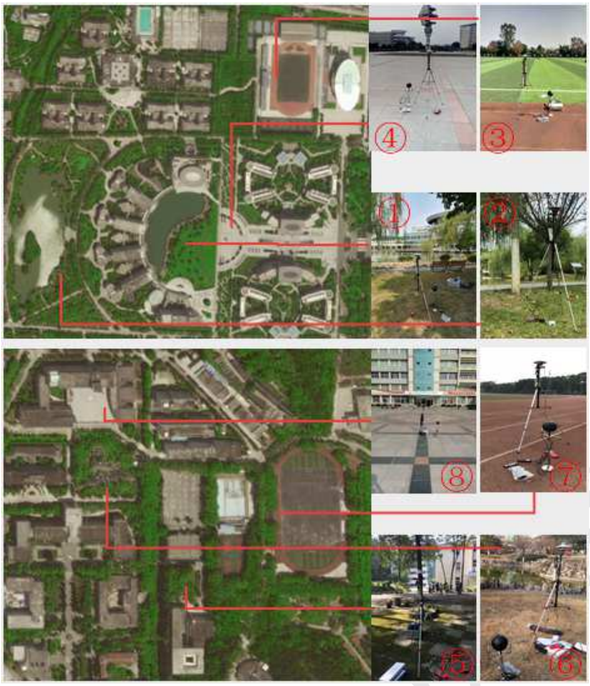

Fig.4. Eight spots for measurement in the campus.

2.2 Data collection

In order to avoid unsuitable weather conditions (rainy or stormy days) for conducting measurements and surveys, the data collection was carried out in sunny days in winter and summer. Table 1 summarizes the measurement date and time. Due to the limitation of manpower and instruments, the measurements were conducted on six days in winter and four days in summer that respectively represent hot and cold conditions in Mianyang based on the local weather forecast. The daily mean air temperatures of the selected summer days are higher than the summer monthly mean air temperatures in that year while the daily mean air temperatures of the selected winter days are lower than the winter monthly mean air temperatures; in other words, the selected days represent the hottest and coldest days in a year. Table 2 describes the surrounding environment of each spot. The winter measurement time was 9: 00 to 17: 00, and the summer measurement time was prolonged by one hour (9:00 - 18:00) due to the delay of sunset and increased outdoor activities. In total, eight spots have been selected for the measurement. Due to the failure of measuring instruments at the spot 8 on the August 29, the analysis of this measuring spot in summer was excluded. Therefore, there are 8 spots in winter and 7 spots in summer that were included in the analysis.

Table 1. The measurement date and time in winter and summer.

Year	**Season**	**Month**	**Date**		**Time**	**Sample size**
			Spots 1-4	**Spots 5-8**		
2018	Winter	Jan.	13, 20, 21	12, 16, 19	9:00-17:00	315
	Summer	Jun.		10	9:00-18:00	208
		Aug.	22, 23	29		

Table 2. The surrounding environment of each spot.

Spots	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Ground surface	Lawn	Lawn	Plastic track	Light-colored marble brick	Brick and grass mixed pavement	Lawn	Plastic track	Light-color marble brick
Shading condition	Shaded	Unshaded	Unshaded	Unshaded	Shaded	Unshaded	Unshaded	Unshaded
Sample size	40	66	59	54	105	59	110	30

Thermal environment parameters include air temperature, relative humidity, wind speed, solar radiation, globe temperature have been recorded in this study. The instruments used to measure the parameters are shown in Table 3. All instruments are in compliance with ISO7726 standard [23]. And all thermal environment parameters were recorded automatically with a 10 min interval and at a height of 1.1 metres.

Table 3. Measuring instruments and accuracy.

Instrument	Measured parameter	Model	Range	Accuracy	Manufacturer
Hand-held weather station	Air temperature	PH-□-C	-50-80 °C	±0.3 °C	XINPUHUI
	Relative humidity		0-100%	±5%	
	Wind speed		0-45 m/s	±0.3 m/s	
Globe temperature probe	Globe temperature	Testo 480	0-120 °C	±0.1 °C	Testo
Solar radiation meter	Solar radiation	JTR05	0-2000 W/m^2	±5%	JANTYTECH

2.3 Questionnaire Survey

Questionnaire survey on thermal comfort and adaptive behaviors were administrated concurrently with the physical measurement. The questionnaire (Table 4) is divided into four parts. Part 1 is a personal information survey, including biological sex and age. Part 2 asks about their clothing and current activity levels. All values are calculated according to ASHRAE 55-2004 [2] and ISO7730 [24] standards. Part 3 asks about participants' thermal sensation, thermal comfort, thermal acceptability and part 4 about their adaptive behaviors to seek comfort. The surveyed participants were students who spent at least 15 minutes at the current measurement spots. A total of 523 completed questionnaires considered as valid responses were collected, with 315 in winter and 208 in summer. The age of respondents was mainly 18-30 years old, accounting for 86.6%; males and females accounted for 54.9% and 45.1% respectively. For the sample size, we had calculated the necessary sample size using G*Power, a software that can compute effect sample sizes for a questionnaire survey. The calculation showed that we should at least collect 105 responses for each gender as well as for shaded or non-shaded spots, with 210 in total to ensure the analysis is valid. Based on the calculation, our sample size is enough to conduct the analysis.

Table 4. The questionnaire used in this study.

Part 1	Biological sex	☐Male ☐Female
	Age	☐<18 ☐18-30 ☐31-45 ☐46-60 ☐>60
Part 2	Clothing Insulation Value (Clo)	Upper Body: ☐T-shirt (0.15) ☐Short-sleeved shirt (0.19) ☐Long-sleeved shirt (0.25) ☐Thermal underwear (0.1) ☐Knitwear (0.28) ☐Hoodie (0.3) ☐Jacket (0.35) ☐Woolen coat (0.45) ☐Wadded jacket (0.5) ☐Down jacket (0.55) Lower Body: ☐Briefs (0.03) ☐Shorts (0.08) ☐Thermal underwear (0.1) ☐Thin trousers (0.24) ☐Thick trousers (0.28) ☐Thin skirt (0.15) ☐Thick skirt (0.25) ☐Dress (0.2) Feet: ☐Thin socks (0.02) ☐Thick socks (0.05) ☐Slippers (0.02) ☐Sandal (0.02) ☐Leather shoes (0.06) ☐Sneaker (0.1)
	Current Activity and Metabolic Rate (W/m^2)	☐Sitting (60) ☐Standing (90) ☐Walking (120) ☐Exercising (360)
Part 3	Thermal Sensation	☐Cold (-3) ☐Cool (-2) ☐Slightly cool (-1) ☐Neutral (0) ☐Slightly warm (1) ☐Warm (2) ☐Hot (3)

	Thermal Comfort	☐Very comfortable (0) ☐Slightly comfortable (1) ☐Comfortable (2) ☐Slightly uncomfortable (3) ☐Very uncomfortable (4)
	Thermal Acceptability	☐Very unacceptable (-2) ☐Just unacceptable (-1) ☐Just acceptable (1) ☐Very acceptable (2)
Part 4	Adaptive Behaviors	☐Using umbrella ☐Wearing a hat ☐Taking on more clothes ☐Taking off clothes ☐Going to a shaded place ☐Staying under the sun ☐No change

2.4 PET calculation

PET is an index for comprehensive evaluation of meteorological parameters based on MEMI (Munich Energy Balance Model for Individuals) and is a physiological equivalent temperature at any given environment (outdoors or indoors). Its value is equal to the air temperature at which, the heat balance of the human body is maintained with core and skin temperatures equal to those under the conditions being assessed [25]. PET is a climate index, meaning that it only depends on the meteorological parameters but not the activity level or clothing.

The first step of calculating PET is to calculate the mean radiant temperature. The mean radiant temperature (T_{mrt}) is a popular parameter used to evaluate thermal comfort or to calculate the radiative heat loss of the human body. The calculation formula of T_{mrt} is [26]:

$$\mathrm{T_{mrt}} = [\left(\mathrm{T_g} + 273\right)^4 + \frac{(1.10\times10^8 \mathrm{v}^{0.6})\left(\mathrm{T_g}-\mathrm{T_a}\right)}{\varepsilon \mathrm{D}^{0.4}}]^{1/4} - 273 \qquad (1)$$

Wherein, T_{mrt} is mean radiant temperature, °C; T_g is globe temperature, °C; T_a is air temperature, °C; v is wind speed, m/s; D is diameter of globe, m (The standard globe with D=0.15 m is used in this paper); ε is the absorption rate of the globe (0.95 in this study).

In this study, PET value was calculated by the air temperature, relative humidity, wind speed, solar radiation, and mean radiant temperature using RayMan model (see details in:[27-29]). The model was frequently used for the assessment of outdoor climates and had been verified by many studies [30-33].

2.5 Data Analysis

In this study, three statistic methods were used for the data analysis, including linear regression, t-test and logistic regression. Linear regression was used to explore relationships between MTSV (Mean Thermal Sensation Vote), MTCV (Mean Thermal Comfort Vote), MTAV (Mean Thermal Acceptability Vote), PTA (Percentage of Thermal Acceptability) and PET to determine neutral temperature, comfort temperature and acceptable temperature range, respectively. T-test was used to determine whether there were significant differences in TSV (Thermal Sensation Vote), TCV (Thermal Comfort Vote) and TAV (Thermal Acceptability Vote) between different biological sexes and shaded (with trees) or non-shaded (without trees) spots. Logistic regression was used to explore the probability of different adaptive behaviors with the change of PET value.

3. Results

3.1 Outdoor thermal environment

The mean, minimum, maximum and SD (Standard Deviation) of thermal environmental data are shown in Table 5-6. The mean value of air temperature, globe temperature and solar radiation of Spot 1 and Spot 5 were much lower than those of other spots because the two measurement spots were under tree crown. Mean relative humidity of these two shaded spots were higher than that of others. Table 7 shows the average T_{mrt} and PET values of each measurement spot in winter and summer. The overall mean T_{mrt} of all spots in winter and summer were 19.8 °C and 44.0 °C, respectively; the overall mean PET of all spots in winter and summer were 16.5 °C and 41.1 °C, respectively.

Table 5. Measured data in winter.

Measuring spot	Air temperature (°C)				Relative humidity (%)				Air speed (m/s)				Globe temperature (°C)				Solar radiation (w/m^2)			
	Mean	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**
1	11.8	5.4	17.6	2.8	58.4	40.5	74.3	9.3	0.3	0	1.4	0.4	13.4	5.2	18.9	3.2	65	19	139	18.8
2	14.1	6.4	21.3	4.0	51.6	31.8	73.1	10.4	0.2	0	1.2	0.3	18.2	6.7	28.0	5.7	234	32	553	132.5
3	15.5	7.6	24.1	4.2	50.1	27.5	69.2	10.8	0.4	0	1.4	0.4	18.0	8.4	28.0	5.2	254	30	589	139.8
4	14.0	7.4	19.9	3.4	52.5	31.0	72.3	10.1	0.3	0	1.5	0.4	17.4	8.5	26.8	5.0	248	19	573	135.9
5	11.3	4.4	16.8	3.1	51.9	40.5	74.7	9.3	0.1	0	1.0	0.2	13.5	5.2	19.7	3.9	78	22	266	49.1
6	17.2	4.2	28.7	6.9	42.5	26.7	75.3	14.2	0.2	0	2.0	0.3	19.2	6.5	29.2	6.7	323	67	544	127.6
7	17.5	6.1	30.2	6.2	41.3	24.5	63.8	9.3	0.5	0	1.5	0.4	18.4	7.6	31.3	5.0	289	60	543	148.1
8	14.5	4.7	23.2	5.4	44.4	29.3	64.0	8.9	0.3	0	1.4	0.4	20.7	7.9	32.8	6.0	326	73	556	128.3
Average	14.5	4.2	30.2	5.1	49.1	24.5	75.3	11.7	0.3	0	2.0	0.3	17.3	5.2	32.8	5.7	227	19	589	152.0

Table 6. Measured data in summer.

Measuring spot	**Air temperature (°C)**				**Relative humidity (%)**				**Air speed (m/s)**				**Globe temperature (°C)**				**Solar radiation (w/m^2)**			
	Mean	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**
1	31.9	26.7	35.7	2.0	56.3	47.3	72.5	6.6	0.3	0	1.4	0.4	32.8	26.9	36.4	2.1	55	27	116	17.3
2	36.4	27.6	44.4	3.4	48.4	33.4	69.5	8.3	0.2	0	1.0	0.3	46.2	33.2	54.6	6.1	694	103	980	261.3
3	38.1	32.5	45.9	3.3	43.8	30.0	66.6	7.9	0.5	0	1.8	0.4	41.7	33.5	49.8	5.2	606	28	968	327.5
4	40.8	32.2	48.1	3.6	41.0	29.7	62.1	7.8	0.3	0	1.4	0.4	44.3	35.8	50.6	3.5	673	112	1022	266.6
5	31.9	23.3	38.2	3.9	50.4	33.7	71.6	10.6	0.1	0	1.2	0.2	34.0	24.4	42.6	3.8	94	29	314	49.8
6	37.0	26.2	46.2	4.7	42.6	26.1	68.5	10.3	0.1	0	1.4	0.3	43.8	30.7	55.8	5.9	685	209	1005	220.5
7	39.0	32.8	45.7	3.4	39.1	26.8	65.3	8.6	0.4	0	1.5	0.4	45.0	33.7	52.9	4.1	699	206	995	187.2
Average	36.4	23.3	48.1	4.7	46.0	26.1	72.5	10.3	0.3	0	1.8	0.4	41.1	24.4	55.8	6.8	501	27	1022	347.7

Table 7. Calculated T_{mrt} and PET.

Measuring spot	Winter								Summer							
	T_{mrt} (°C)				**PET (°C)**				**T_{mrt} (°C)**				**PET (°C)**			
	Mean	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**
1	15.2	5.2	25.5	4.8	12.8	4.6	19.3	3.0	33.5	27.1	38.9	2.3	33.0	27.0	36.8	2.3
2	20.7	6.7	42.4	8.0	17.3	5.7	26.9	5.1	50.0	31.7	76.9	10.0	44.7	33.9	58.9	5.6
3	20.8	8.8	42.5	7.5	16.9	7.1	26.8	4.9	45.6	33.7	68.7	8.6	42.7	33.7	53.9	5.8
4	20.9	8.5	41.5	8.6	16.6	7.1	25.4	4.4	46.7	35.8	59.3	5.1	44.6	35.5	52.5	3.9
5	14.6	5.2	25.8	4.8	13.2	4.7	19.4	3.7	34.7	24.4	43.1	4.1	33.9	24.8	40.4	3.5
6	20.4	6.5	36.4	7.6	18.9	5.1	29.3	6.7	46.4	30.7	64.0	8.2	42.7	30.2	52.2	5.4
7	19.8	7.6	42.3	5.4	17.1	6.5	30.7	5.6	51.0	33.7	74.0	8.5	46.0	34.1	55.3	5.0
8	25.7	7.9	52.8	10.0	19.1	6.4	32.2	6.0	-	-	-	-	-	-	-	-
Average	19.8	5.2	52.8	8.0	16.5	4.6	32.2	5.5	44.0	24.4	76.9	9.7	41.1	24.8	58.9	6.8

3.2 Thermal sensation

Figure 5 shows the frequency distribution of thermal sensation vote (TSV) of the respondents in winter, summer and two seasons. The results show that the proportion of "neutral" sensation in winter (44.8%) is much higher than that of other sensation; in summer, the highest proportion (32.7%) of respondents voted for "slightly warm", followed by respondents voting for "warm" and "neutral", accounting for 29.3% and 24.5% respectively; when two seasons are combined, "neutral" sensation still took the highest proportion of 36.7%.

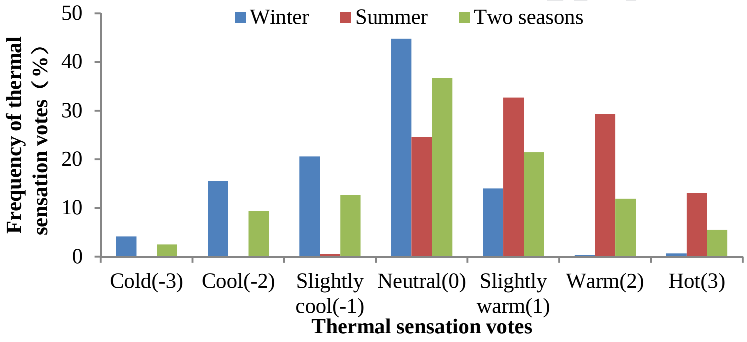

Fig.5. Frequency distribution of thermal sensation votes in different seasons.

Separate linear regression models in winter and summer were established between TSV and PET (Equation 2-3), where SE is standard error. Respondents' TSV was binned by PET interval of 1 °C in winter and 2 °C in summer. The mean TSV (MTSV) in each PET bin served as the dependent variable with the central PET of each bin as the independent variable. Figure 6 shows the relationship between MTSV and PET in each season.

Winter: $MTSV = 0.0948PET-2.2275$ ($R^2 = 0.815$, $SE = 0.314$, $F = 92.495$, $Sig. = 0.000$) (2)

Summer: $MTSV = 0.0718PET-1.6383$ ($R^2 = 0.868$, $SE = 0.244$, $F = 78.927$, $Sig. = 0.000$) (3)

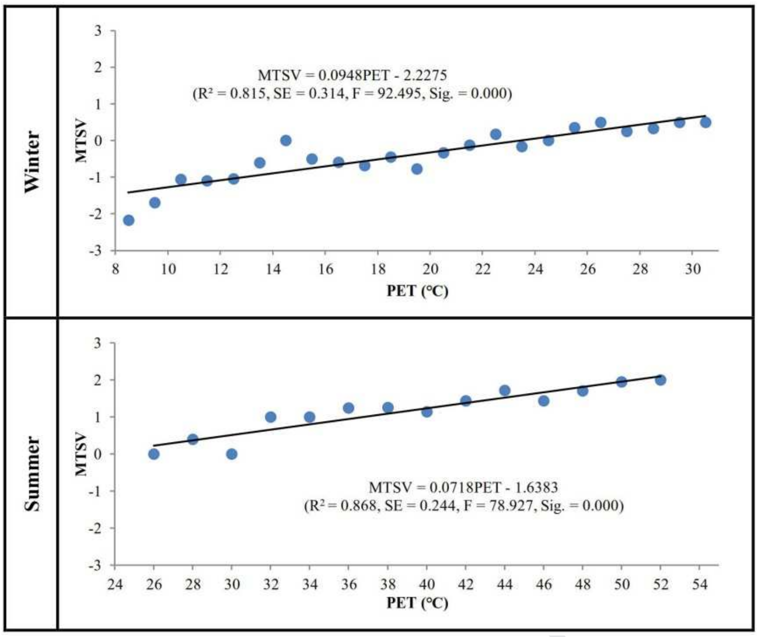

Fig.6. Relationship between MTSV and PET.

The slope of regression line was 0.0948 in winter and 0.0718 in summer, which means that PET change of 10.6 °C in winter and 13.9 °C in summer may result in one scale of TSV change. Clearly, people are more sensitive to temperature change in winter than in summer. Neutral temperature is defined as the temperature at which the MTSV is zero, which corresponds to a neutral thermal sensation. By solving the Equation 2 and 3, the outdoor neutral temperature in Mianyang can be calculated as 23.5 °C in winter and 22.8 °C in summer.

3.3 Thermal comfort

Figure 7 shows the frequency distribution of thermal comfort votes. The frequency of "comfortable" votes is the highest in each season, accounting for 44.1%, 36.5% and 41.1% of the total voting frequency in winter, summer and two seasons, respectively. The sum of "comfortable" and "slightly comfortable" votes accounts for the majority of the total votes in each season, which is 84.4% in winter and 66.3% in summer, respectively, indicating that most people thought that the thermal environment of the outdoor activity space was comfortable; the votes of "very uncomfortable" and "very comfortable" only account for a small percentage of the votes per season. At the same time, the non-neutral thermal sensation vote in summer is obviously more than that in winter, which leads to more uncomfortable votes ("very uncomfortable" and "slightly uncomfortable") in summer than in winter.

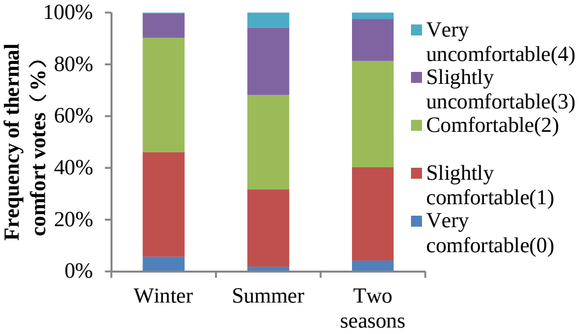

Fig.7. Frequency distribution of thermal comfort votes in different seasons.

The relationship between MTCV and PET in winter and summer is shown in Figure 8 as plotted with the equations as follows. It can be found that the MTCV and PET show a quadratic function relationship, which is different from the linear correlation between MTSV and PET. The most comfortable PET in winter is 30.4 °C, which is 6.9 °C higher than the neutral PET in the same season. The most comfortable PET was not found in summer; generally, the lower the PET, the more comfortable the respondents felt.

Winter:

$MTCV = 0.0018PET^2-0.1094PET+2.9251$ ($R^2 = 0.5027$, SE = 0.289, F = 10.107, Sig. = 0.001) (4)

Summer:

$MTCV = -0.0014PET^2+0.1708PET-2.5224$ ($R^2 = 0.8149$, SE = 0.269, F = 24.218, Sig. = 0.000) (5)

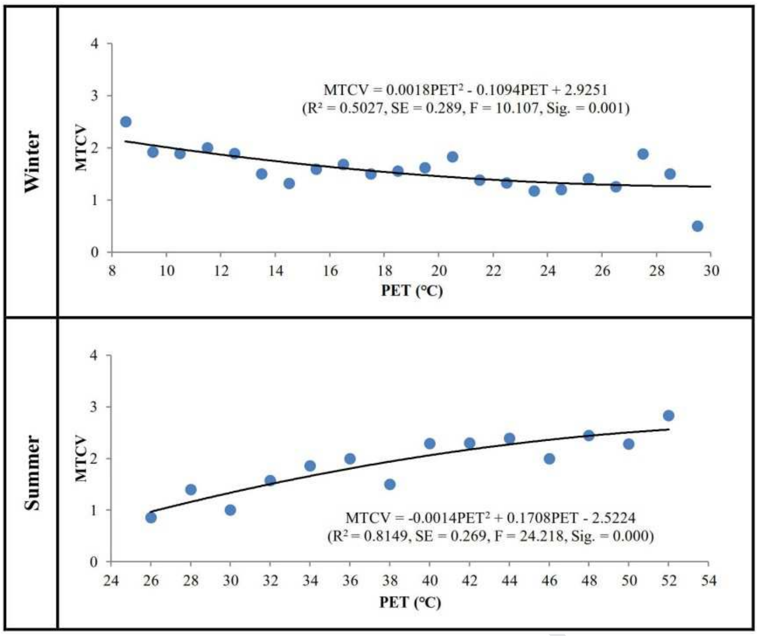

Fig.8. Relationship between MTCV and PET.

3.4 Thermal acceptability

In order to understand the thermal acceptability and percentage of thermal acceptability at different temperatures for different seasons and throughout the year, MTAV and PTA were calculated at the interval with 1 °CPET for winter, 2 °CPET for summer and 2 °CPET for the whole year, and the relationships are shown in Figure 9. The results showed that MTAV and PET were linearly correlated in winter and summer. With the increase of PET in winter, the acceptance of respondents to temperature increased gradually; however, with the increase of PET in summer, the acceptance of respondents to temperature decreased gradually. Quadratic function relationship occurred between PTA and PET. ASHRAE 55 recommends that the thermal environment acceptable to 90% of the population is a comfortable thermal environment. According to this criterion and the equations of PTA and PET, the temperature range acceptable to 90% populations is PET ≥ 20.2 °C in winter, PET ≤ 35.6 °C in summer and 20.5 °C ≤ PET ≤ 35.7 °C in the whole year.

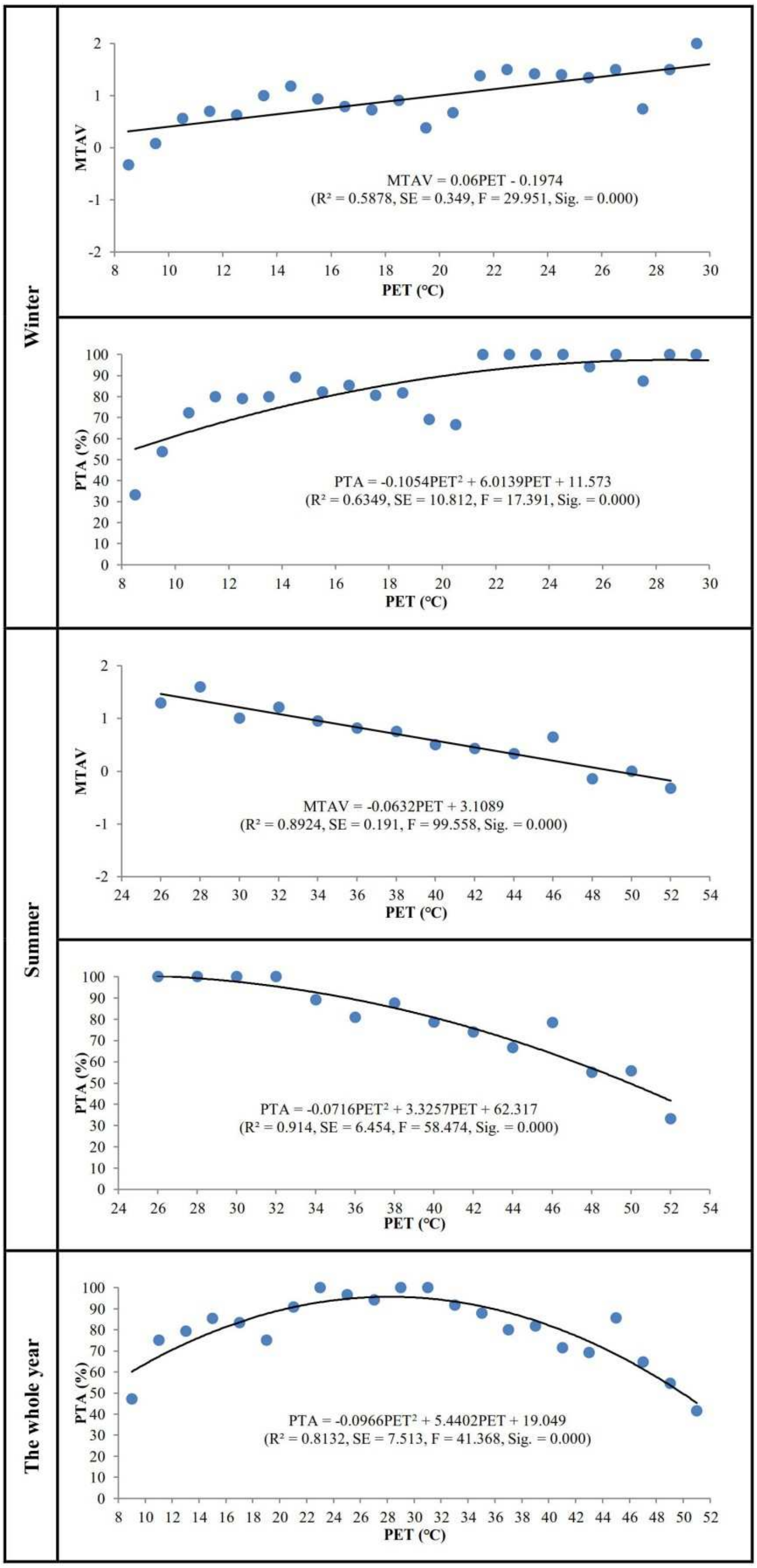

Fig.9. Relationship between MTAV, PTA and PET in different seasons.

3.5 Shading

T-test of two independent samples was carried out for TSV of shaded and non-shaded points to find out whether shading has affected TSV of respondents. Results indicated that the mean value of TSV in shaded and non-shaded points in winter were -0.82 and -0.37 respectively with the test statistics t = -3.137 (Sig. = 0.002). When the significance level is 0.05, it is believed that TSV of shaded and non-shaded measuring points in winter had a significant difference and shading significantly affected TSV in winter. In summer, the mean value of TSV in shaded and non-shaded points were 1.07 and 1.42 respectively with the test statistics t = -2.483 (Sig. = 0.014). It is indicated that TSV in shaded and non-shaded points in summer differed significantly and that shading also significantly affected TSV in summer. Meanwhile, TSV of non-shaded points both in winter and summer was higher than that of shaded points, which indicates that non-shaded points gave people a stronger thermal sensation.

T-tests results also showed that TAV in shaded and non-shaded points in winter did not differentiate significantly (Sig. > 0.05). However, TAV of shaded points is significantly different from that of non-shaded points in summer (Sig. = 0.000), and people's thermal acceptability in shaded places is significantly higher than that without shading. T-tests results further indicated that TCV in shaded and non-shaded points in winter did not differentiate significantly (Sig. > 0.05); while TCV in shaded and non-shaded measuring points in summer was significantly different (Sig. = 0.020), indicating that shading might significantly affect TCV of respondents in summer and shaded measuring points made people feel more comfortable.

3.6 Biological sex

Because of the difference of the basic metabolic rate and physiological structure, as well as the difference of physiological and psychological response to many kinds of environmental factors, the evaluation and requirements of male and female students for the outdoor thermal environment are not completely the same. T-test results of different biological sexes indicated that the mean value of TSV of male and female were 0.28 and 0.17 respectively. The test statistics $t = 0.988$ (Sig. = 0.324), and the two-tailed P value is higher than the significance level $\alpha = 0.05$, indicating that difference of biological sex might not have a significant impact on the respondent's TSV. T-test is also carried out for TCV of different biological sexes. The analysis results showed that mean value of TCV of male and female were 1.81 and 1.71 respectively with the statistics $t = 1.281$ (Sig. = 0.201), indicating as similar result with TSV that biological sex difference might not significantly affect TCV.

Results of t-test for TAV of different biological sexes showed that mean value of TAV of male and female were 0.6969 and 0.8814 respectively with the test statistics $t = -2.057$ (Sig. = 0.040), indicating that biological sex difference might significantly affect TAV. The TAV of female was significantly higher than that of male, indicating that female could accept the thermal environment better than male.

3.7 Activities and clothing insulation

Table 8 shows the respondents’ average activity and clothing insulation value. The average activity in summer is slightly larger than that in winter (110 W/m^2 and 96 W/m^2, respectively), indicating that the people prefer outdoor activities in summer. At the same time, the clothing insulation value changes with the season and the average values of winter and summer are 1.33 Clo and 0.51 Clo, respectively. Figure 10 shows the change of average clothing insulation value and activity with PET value. When PET value increases from 8 °C to 52 °C, the average clothing insulation value of respondents change from 1.35 Clo in winter to 0.5 Clo in summer, and the average activity changes from 93 W/m^2 in winter to 127 W/m^2 in summer. But the change of average clothing insulation value and activity with PET value is not obvious in each season internally.

Table 8. Average activity and clothing insulation value.

Measuring point	**Activity (W/m^2)**				**Clothing insulation value (Clo)**			
	Winter		**Summer**		**Winter**		**Summer**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
1	78	23.856	78	25.622	1.37	0.077	0.49	0.056
2	106	63.636	119	54.876	1.33	0.116	0.53	0.055
3	119	78.866	202	121.713	1.26	0.202	0.50	0.089
4	115	13.631	124	53.745	1.35	0.072	0.49	0.046
5	88	27.088	67	17.886	1.36	0.071	0.52	0.072
6	91	28.109	107	59.422	1.32	0.115	0.51	0.073
7	77	41.673	113	96.911	1.35	0.093	0.52	0.068
8	111	19.538	-	-	1.31	0.138	-	-
Sum	96	46.023	110	79.165	1.33	0.118	0.51	0.068

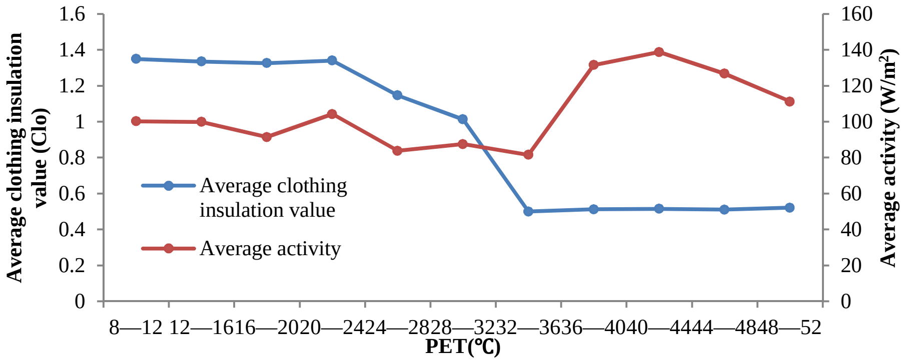

Fig.10. The change of average clothing insulation value and activity with PET value.

3.8 Adaptive behaviors

The survey results of adaptive behaviors in summer and winter are shown in Figure 11. As shown in the figure, "going to a shaded place" and "staying under the sun" were considered the best measures to improve current thermal comfort in summer and winter, respectively, and the proportion was far more than other options. It showed that improving the objective environment as much as possible was more comfortable than subjective adjustment.

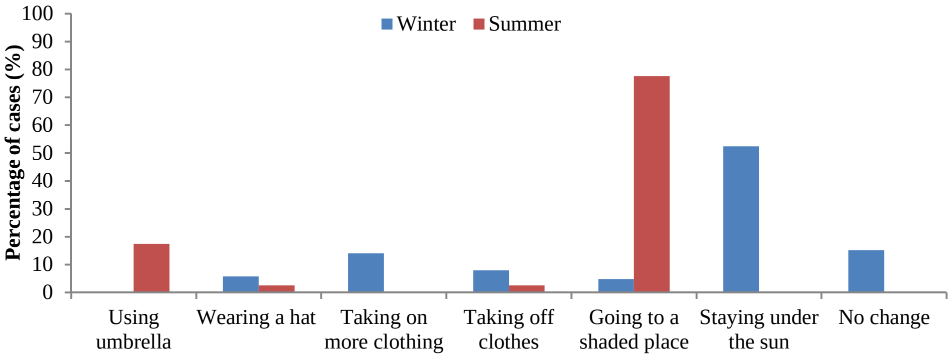

Fig.11. Frequency distribution of adaptive behaviors.

In order to explore the probability of people taking different measures with the change of PET value, taking the votes of six group measures as the dependent variable and PET value as the independent variable, a regression analysis was conducted using binary Logistic regression model in SPSS software, and the fitted model was tested using goodness-of-fit test statistics of Hosmer and Lemeshow. The regression equation and test results are shown in Table 9. The significant level α is set to 0.05. If the probability p value is less than α, the difference between the predicted value of the model and the observed value is quite large; if the probability p value is greater than α, the difference between the predicted value of the model and the observed value is small, and the probabilistic model has a better explanation. It can be seen from the table that the probabilistic models of "wearing a hat" and "taking on more clothes" have no explanation effect, but the probabilistic models of other measures are meaningful. By further observing Exp (B), namely OR (Odds Ratio), it is shown that when PET increases one degree Celsius, the probability that the people take three measures ("using umbrella", "taking off clothes" and "going to a shaded place") to improve thermal comfort will be increased by 22.6%, 4.9% and 16.6%, respectively; the probability that the people take the measure of "staying under the sun" to improve thermal comfort will be decreased by 17.5%. This further verifies the problem reflected in the frequency distribution in Figure 11, that is, people prefer to obtain the better thermal comfort by improving the surrounding objective environment rather than taking measures to make the subjective adjustment. And with the increase in PET, people prefer to "using umbrella" rather than "taking off clothes" to improve thermal comfort, possibly because in hot summers, the clothing insulation (0.51 Clo) of people is already the lowest and the possibility of adjusting body temperature and improving thermal comfort by further taking off clothes is morally unacceptable.

Table 9. Logistic regression models for adaptive behaviors.

Adaptive behaviors	**Logistic model**	**Test of Hosmer and Lemeshow**			**Exp(B)**
		Chi-square	**df**	**P**	
Using umbrella	Log*it*(p) = 0.204PET-7.499	4.962	7	0.665	1.226
Wearing a hat	Log*it*(p) = -0.016PET-0.613	20.049	8	0.010	0.984
Taking on more clothes	Log*it*(p) = -0.222PET+3.821	18.230	7	0.011	0.801
Taking off clothes	Log*it*(p) = 0.048PET-1.843	2.591	8	0.957	1.049
Going to a shaded place	Log*it*(p) = 0.153PET-4.211	3.486	8	0.900	1.166
Staying under the sun	Log*it*(p) = -0.193PET+4.699	10.453	8	0.253	0.825

4. Discussion

4.1 Neutral temperature

According to the above analysis, the neutral PET in winter and summer in Mianyang area of China was 23.5 °C and 22.8 °C, respectively. The neutral PET in summer was 0.7 °C lower than that in winter, while the average activity in summer (110 W/m^2) was higher than that in winter (96 W/m^2). This indicates that as the seasons change, people are constantly adjusting their thermal sensation to adapt to the current thermal environment; the high-intensity activities in summer may increase people's thermal sensation towards lower temperature preference and cause a decrease in neutral temperature. Table 10 shows the results of other relevant studies. Similar results were found in Sydney [34] and Damascus [35] where the neutral PET in summer was lower than that in winter. Different results were obtained in Cambridge [36], Taiwan [37], Tel Aviv [38], and Harbin [39]. From winter to summer, with the change of seasons, the neutral PET of population increased gradually. Observably, the neutral PET in Mianyang in winter was closer to that in Taiwan, and the neutral PET in summer was closer to that in Sydney. Different climatic conditions, ethnicities and cultural customs are all possible factors leading to the difference of neutral temperature in different regions.

Table 10. Neutral temperature in other relevant studies.

Region	**Context**	**Temperature index**	**Neutral temperature**	
			Winter	**Summer**
Sydney (2003)[34]	Outdoor and semi-outdoor	PET	28.8 °C	22.9 °C

	spaces			
Damascus (2013)[35]	Residential areas and parks	PET	24.2 °C	15.7 °C
Cambridge (2001)[36]	Urban squares, streets and parks	Ta	7.5 °C	27 °C
Taiwan (2009)[37]	Public square	PET	23.7 °C	25.6 °C
Tel Aviv (2013)[38]	Urban parks	PET	22.7 °C	23.9 °C
Harbin (2018)[39]	University campus	PET	18.0 °C	20.0 °C

4.2 Comfort temperature

The research results showed that the "neutral" thermal sensation was not the most comfortable status perceived by the respondents in different seasons, and the most comfortable PET in winter was 30.4 °C, 6.9 °C higher than the neutral temperature. The most comfortable PET was not found in summer, but the lower the PET, the more comfortable the respondents felt. This is consistent with the research conducted in Tianjin [41] where the most comfortable condition was TSV in the cold season at 0.86 and TSV in the hot season at -1.07. This phenomenon could be explained by a concept called "Alliesthesia" [34], a psychological mechanism that causes seasonal sensation differences. In cold seasons, warm feelings are considered more comfortable than cool ones and vice versa.

4.3 Acceptable temperature range

It was found that 90% acceptable temperature range of the whole year in Mianyang area was 20.5 °C ≤ PET ≤ 35.7 °C. The acceptable temperature range from other studies is shown in Table

11. The lower limit of acceptable temperature in Mianyang is close to that of Taiwan, and the upper limit is slightly higher than that of other regions. This might be due to the bias of a particular group (students who were playing or just played football) selected in the survey. Their active engagement with sports significant pushed their upper limit of acceptance of temperature. Meanwhile, these results and comparison also indicate that there are significant differences in heat tolerance among different population groups in different regions. People living in cold areas such as Harbin [39] have stronger tolerance to low outdoor temperature than other regions.

Table 11. Acceptable temperature range in other relevant studies.

Region	**Context**	**Temperature index**	**Acceptable temperature range**
Taiwan (2009)[37]	Public square	PET	21.3 °C-28.5 °C
Tel Aviv (2013)[38]	Urban parks	PET	19 °C-25 °C
Guangzhou (2016)[42]	Residential communities	PET	18.1 °C-31.1 °C
Harbin (2018)[39]	University campus	PET	2.5 °C-30.9 °C

4.4 Effects of shading and biological sex

According to the t-test results, shading might significantly affect the TSV of respondents in winter and summer, and the TSV in non-shaded measuring spots both in winter and summer was higher than that with shading. This is mainly because that places without shading accept shortwave solar radiation, which results in surrounding air temperature and globe temperature being higher than that with shading (Table 5) and then increase people’s thermal sensations. The analysis also showed that shading might not significantly affect the TCV and TAV of respondents in winter but might significantly affect that in summer. Shaded places were more comfortable and acceptable in summer. The results echo the studies from Lin [43] who indicated that highly shaded places caused discomfort in winter and barely shaded places caused discomfort in summer.

The results of t-test for TSV and TCV of different biological sexes showed that biological sex might not be associated with TSV and TCV. This result is different from that of Donnini [44] and de Paula Xavier [45]. They carried out investigation of the neutral temperature of different biological sexes in southern Quebec and Brazil respectively and founded that the neutral temperature of female was 0.3 °C and 0.1 °C higher than that of male. The effect of biological sexes on thermal sensation may be subjected to regional difference and the population type. However, the results of t-test for TAV of different biological sexes showed that biological sex difference might significantly affect TAV and the TAV of female was significantly higher than that of male, indicating that female could accept the thermal environment better than male. The one possible reason is that clothing insulation value of female (1.01 Clo) and male (1.00 Clo) is almost the same while the activities of female (97 W/m^2) and male (106 W/m^2) is rather different; under this circumstance, the high-intensity activities of male might result in a lower TAV.

4.5 Adaptive behaviors

The adjustment of clothing is an important adaptive behavior to improve the thermal comfort of people, which has been confirmed by many studies [46-48] showing that there was a significant correlation between the clothing insulation value and temperature. The clothing insulation value decreases with the increase of the temperature and vice versa. However, in the same season, the change of clothing insulation value with temperature was not significant, which has also been confirmed in the research of Lin [37].

The variation of outdoor activity with seasons is also demonstrated in this research. Outdoor activity level in summer was higher than in winter, indicating that students tend to do exercise in outdoor environments in summer while in winter when outdoor environments are cold, they reduce the outdoor activities and tend to stay indoors.

5. Conclusions

In this paper, outdoor thermal comfort and adaptive behaviors in a university campus in Mianyang, China was investigated. The results showed that mean value of PET was 16.5 °C in winter and 41.1 °C in summer. The neutral PET in winter and summer were 23.5 °C and 22.8 °C, respectively, and the thermal sensation was more sensitive in winter than in summer. The most comfortable PET in winter was 30.4 °C; while in summer, the lower PET value, the more comfortable the respondents felt. The acceptable temperature ranges for 90% of the population were PET ≥ 20.2 °C in winter, PET ≤ 35.6 °C in summer and 20.5 °C ≤ PET ≤ 35.7 °C in the whole year. According to the t-test results, shading might significantly affect the TSV of respondents in winter and summer; it might not significantly affect the TCV and TAV of respondents in winter but might significantly affect that in summer. The results of t-test also showed that biological sex might not be associated with TSV and TCV, but it might significantly affect TAV; the TAV of female was significantly higher than that of male, indicating that female could accept the thermal environment better than male.

The average activity and clothing insulation value of respondents were 96 W/m^2 and 1.33 Clo in winter, and 110 W/m^2 and 0.51 Clo in summer. In different seasons, the average activity increased with the increase of PET, and the clothing insulation value decreased with the increase of PET. If PET was increased by one degree Celsius, the probability that people improve thermal comfort by "using umbrella", "taking off clothes" and "going to a shaded place" was increased by 22.6%, 4.9% and 16.6%, respectively, while the probability of "staying under the sun" was reduced by 17.5%.

This research enriches literature of outdoor thermal comfort in hot summer-cold winter regions, and provides a reference for relevant standards, such as National Assessment Standard for Green building [49] where Section 8 “Environment Livability” addresses the outdoor thermal comfort issue. At the same time, it expands the theoretical research of outdoor activity space planning and design on campus based on climate adaptability. The research has three limitations: (1) This research has only measured outdoor climates in hot summer and cold winter while missing other seasons; (2) The measurement period for each season is short (six days in winter and four days in summer); (3) Most of the respondents are 18-30 years old university students while missing other groups of campus users. For a more holistic understanding of the outdoor thermal comfort in this climate, it is necessary to expand the measurement period to cover a whole year including spring and autumn to see the transition of thermal sensational changes in a year; it is also important to expand the measurement days in each season to see the influence from other climatic parameters such as air velocity and relative humidity; since academic and administrative staff are also important users of a campus open space, the thermal comfort studies should be more inclusive of sampling in terms of age; although the sample size in this study is sufficient to conduct the t-test analysis, it is necessary to expand the sample size for more advanced statistical analyses with stronger evidence. In addition, the thermal sensation of the population is obtained by questionnaire survey, while some individual respondents may not describe the current thermal state well. With the development and progress of technologies, wearable smart devices can be used to accurately measure certain physiological parameters of the population and combine them with thermal conditions. In the aspect of the adaptive behavior, the future research can further quantitatively analyze the changes of thermal comfort with different improvement measures by means of ANOVA analysis and multiple comparison tests.

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Thermal comfort in campus outdoor spaces in hot summer and cold winter climate were studied.

Respondents preferred "slightly warm" in winter and "slightly cool" in summer.

Acceptable PET (Physiologically Equivalent Temperature) was identified for different seasons.

When PET increased by one unit, the probability of a series of adaptive behaviours was identified.

Neutral temperatures in different seasons were compared and biological sex differences were examined.