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Thermal Comfort in the Overhead Public Space in Hot and Humid Climates: A Study in Shenzhen

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Abstract: In recent years, semi-outdoor space has become an important research subject in the field of thermal comfort. Overhead space located on the ground floor is a common type of semi-outdoor space in China's Lingnan region with a hot and humid climate. Its thermal comfort has been scarcely studied. This study aims to reveal the importance and influencing factors of overhead public spaces in hot and humid areas, and to explore the corresponding adaptive behaviors of people. In this research, several overhead public spaces in Shenzhen University were selected to conduct field measurements and questionnaire surveys (n = 509) in hot and cold seasons. The results indicated that the acceptable physiologically equivalent temperature (PET) range for 90% of the population was 26.2–30.4 °C in hot season, 9.9–19.2 °C in cold season, and 17.6–25.3 °C for the whole year. The respondents preferred "neutral" in cold season and "slightly cool" in hot season. Respondents in hot season were more eager to adjust their thermal comfort, while those in cold season were more comfortable exposing themselves to the sun. Concurrently, the neutral temperature and neutral temperature range for different seasons was obtained and compared with the results of other studies. The results provide references for thermal comfort adjustment in hot and humid areas as well as optimization suggestions for the planning and design of overhead spaces.

Keywords: outdoor thermal comfort; semi-outdoor space; hot and humid climate regions; overhead spaces; adaptive behaviors

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1. Introduction

Moderate outdoor activities are beneficial both physiologically and psychologically. They have been shown to enhance subjective well-being and pathogen resistance [1], reduce myopia in adolescents [2], delay cognitive decline in the elderly [3], decrease individual susceptibility to symptoms of mental illness, and improve emotional or cognitive states [4], etc. Urban open spaces have substantially improved the quality of life for citizens from the aspects of physical, environmental, social, and economic benefits [5]. In outdoor and semi-outdoor spaces, human thermal satisfaction is significantly affected by the local microclimate [6], and the level of thermal comfort can greatly influence how often people choose to use these spaces [7]. Many cities are endeavoring to control the local climate and microclimate in urban environments to reduce thermal stress and improve living conditions [8]. Therefore, the research on outdoor and semi-outdoor thermal comfort is of important significance to promote the overall health status of the users and create a better human habitat.

Semi-outdoor spaces can be defined as spaces partially open to the outdoor environment [9]. They are often attractive and frequently used spaces that have a great influence on the quality of life and well-being of users [6,10]. Generally, users expect a thermal environment different from indoor and outdoor ones [11]. Semi-outdoor spaces have significantly lower air temperature and mean radiant temperature than outdoor spaces, providing a more comfortable outdoor thermal environment [12]. Overhead spaces are a type of semi-outdoor spaces. According to the Design Code for Residential Buildings GB50096-2011 [13], the overhead floors refer to the open space layers with only structural support and no external envelope structure. Canopies and balconies in buildings do not fall under the concept of overhead spaces. Overhead space in buildings have many advantages, including greater moisture-proofing and ventilation, sun and rain protection, noise reduction and energy saving. Especially in the special context of the normalized pandemic prevention and control in China, overhead spaces on the ground floor (Figure 1) can also serve as suitable places for nucleic acid testing in summer when the excessive heat makes the outdoor areas uncomfortable and stressful for staying and waiting.

Figure 1. Nucleic acid test being conducted in an overhead space on the ground floor (Photos taken by the authors).

Currently, some scholars have conducted studies in the field of semi-outdoor thermal comfort. These studies have been carried out in different climatic conditions, such as tropical [14–16], subtropical [17,18], highland [19], Mediterranean [20], desert [21], and continental [22] climates. At the same time, they covered diverse space types, such as semi-outdoor learning spaces in colleges and universities [23], office buildings [24], cafeterias [25], stadiums [26], and bus shelters [27]. In recent studies in hot and humid regions, some scholars compared thermal comfort differences among indoor, semi-outdoor, and outdoor spaces. Mihara et al. [28] conducted an experiment in an air-conditioned room and semi-outdoor space in Singapore to evaluate environment satisfaction, mood and cognitive performance in cool and warm seasons and used the structural equation model (SEM) to analyze the relationship among environment satisfaction, mood, and work performance. Acero et al. [12] measured and compared thermal comfort in outdoor and semi-outdoor spaces in Singapore, indicating that semi-outdoor spaces were effective in reducing air temperature and mean radiation temperature. Othman et al. [29] studied pedestrian thermal comfort in outdoor and semi-outdoor conditions in two Malaysian universities and obtained neutral temperatures of 28.1 °C and 30.8 °C, with the acceptable physiologically equivalent temperature (PET) ranges of 24–34 °C and 26–33 °C, respectively.

Simultaneously, there are also studies on the relationship between spatial forms and thermal comfort in semi-outdoor spaces. Gamero-Salinas et al. [30] found that semi-outdoor spaces could serve as thermal buffers and that the building forms in semi-outdoor spaces were related to microclimate and thermal comfort in hot and humid climates. Tao et al. [23] explored the relationships among thermal environment, thermal perception, and spatial settings with five semi-outdoor spaces on the campus in Singapore, suggesting that increasing the height of the space and surrounding buildings could improve user's satisfaction with semi-outdoor spaces, and that building orientation and headspace void-to-solid ratio could effectively regulate temperature and air velocity, respectively. In addition, some studies further investigated the possible factors affecting thermal comfort in semi-outdoor spaces. Pinto et al. [31] conducted a study in a public transport building in Porto and proposed a ventilation model (aDR) to assess the local thermal discomfort caused by ventilation in semi-outdoor spaces. Yin et al. [32] selected an outdoor space in a university in Xi'an to explore the effects of the acoustic environment on thermal comfort, thermal environment on acoustic comfort, and thermoacoustic factors on overall comfort. Concurrently, some scholars studied the adaptive behaviors of people in thermal discomfort. Huang et al. [33] studied outdoor thermal comfort and adaptive behaviors at a university in Mianyang, a hot summer and cold winter region, and found that when PET increased by 1 °C, the probability of "using an umbrella", "taking off clothes", and "seeking shade" increased by 22.6%, 4.9%, and 16.6%, respectively. Nakano et al. [34] investigated thermal adaptation characteristics and thermal comfort zones in semi-outdoor environments in Tokyo and found that clothing adjustment was the primary form of behavioral adaptation and that occupants in semi-outdoor environments could tolerate thermal environments 2–3 times wider than the range obtained by the predicted percentage dissatisfied (PPD).

Although the thermal comfort in outdoor spaces has been evaluated under various climatic conditions, the possible factors affecting thermal comfort are yet to be fully understood in the hot and humid climate. Furthermore, more semi-outdoor space types should be included to propose environmental design strategies that help to reduce the negative impact of excessive heat stress in summer. Among them, overhead space is a typical semi outdoor space that can improve the thermal environment. In China, the research on overhead public spaces is mainly divided into two directions. One is focused on the design of the overhead spaces [35,36], and the other is focused on the wind environment of the overhead spaces [37,38], which lacks the integration of design and environmental performance studies. In addition, different cities have different policies on the reward of plot ratio of overhead public spaces. It is found that the planning and design of overhead public spaces is a relatively new field in the practice and related research, and the relevant design theories and methods need to be further improved through research and practice. The Lingnan region (south of the Nanling Mountains) in China has a humid subtropical monsoon climate with a high mean annual temperature, massive precipitation, and intense solar radiation. Due to its hot and humid climate, many traditional dwellings have been ventilated and insulated by various means since ancient times [39]. A study in Guangzhou showed that the standard effective temperature index could be reduced by 6~10 °C using semi outdoor components, such as pilotis (a support that lifts a building to the ground or above a water body) [40]. In modern times, the architectural form of "Qilou" (riding tower) has emerged in Lingnan. As a type of overhead space, it reflects the artistic features combining Chinese and Western elements under the climatic and historical background of the region. Although the overhead floors are often observed in Lingnan architecture and extensively used by architects as an architectural design strategy to cope with a hot and humid climate, their effectiveness and practical use effects have not yet been verified from the user's perspective.

In sum, there is a lack of research on the thermal comfort of overhead space, especially in hot and humid areas, and overhead space itself exists widely in hot and humid areas. The research of overhead space is still a relatively new field and needs further exploration in terms of design and planning. Therefore, the main objectives of this study are proposed as follows: (1) To investigate the thermal sensations of users in the overhead public space in hot summer and warm winter regions and compare with previous semi-outdoor thermal comfort studies. (2) To explore various factors that may affect thermal comfort in the overhead public space, (3) To study the adaptive behaviors of users seeking thermal comfort in the overhead public space. This study is expected to supplement the research on thermal comfort and adaptive behaviors of semi-outdoor spaces in hot and humid areas, especially to enhance the application of overhead spaces in college campuses. From the architectural design perspective, it provides suggestions for thermal comfort adjustment in hot and humid areas such as Shenzhen and optimizes and promotes the planning and design of overhead spaces.

2. Materials and Methods

2.1. Region Selection

The application of overhead spaces has become increasingly common and mature in southern Chinese cities. Shenzhen is a mega-city in southern China and the smallest first-tier city in China, with a fast construction speed and high plot ratio. It lays a sound foundation for the practice of overhead spaces. According to China national climate classification criteria, five major climate zones are identified for building design. Shenzhen is located in a hot summer and warm winter region, where the mean temperature of the coldest month is above 10 °C, the mean temperature of the hottest month is 25–29 °C, and the number of days with mean daily temperature above 25 °C is 100–200.

Shenzhen University (SZU) is a representative comprehensive university in the Lingnan region with a large number of students. The campus was built relatively recently, with diversified architectural forms and distinctive semi-outdoor spaces. The ambiguity and multiplicity of overhead spaces make it a special type of open spaces used the most frequently on the campus. Hence, SZU was selected as the study area in this research. SZU campus (113.6° E, 22.3° N) is located in the southern part of Guangdong Province, China. According to the local meteorological records, the outdoor air temperature varies between 5 °C and 37 °C, with the highest annual mean outdoor air temperature in July (28 °C) and the lowest in February (15 °C) [41]. In this study, the student dormitory area (completed in 2019) in the Zhai zone (Figure 2) with relatively high traffic in SZU was selected as the study object. Table 1 shows the basic information on the measurement sites. Figure 3 shows the site selected for the study. Points 1 and 2 are a study and rest space respectively with some tables and chairs. The area of point 2 is slightly smaller than that of point 1, and there is a piano room. Point 3 is a passage space, without tables and chairs, with the largest area. Point 4 and point 5 serve as the Express Center together. Point 4 is the entrance space of the Express Center, which is used for queues, waiting, etc. Point 5 is the container area of the Express Center.

Figure 2. The campus and site information. (Photos taken by the authors).

Table 1. Information on the measurement sites.

Site	Floor	Floor Height (m)	Depth (m)	Width (m)	Orientation
1	Ground	4.4	19.3	27.0	East-West
2	Ground	4.4	19.3	13.6	South-North
3	Ground	4.4	19.3	19.2	South-North
4	Semi underground	4.4	17.2	20.0	East-West
5	Semi underground	4.4	16.0	10.0	South-North

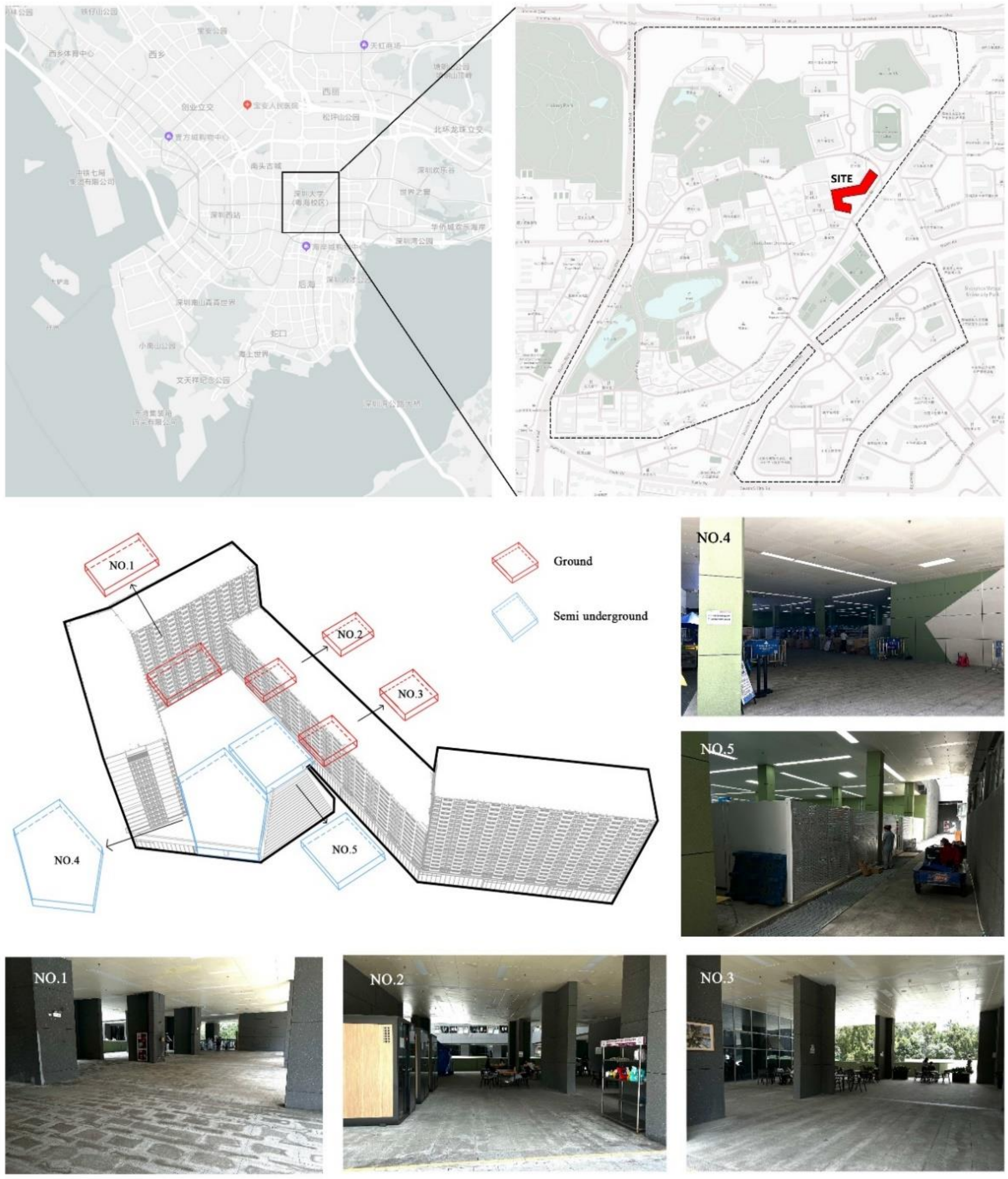

Figure 3. Study site selection.

2.2. Meteorological Data

Given the dates when the majority of students start school, the actual measurement dates in this paper were from 23 September to 6 October 2021 in hot season and from 3 January to 7 January 2022 in cold season. Data were kept only on sunny days to eliminate the interference of other factors. Each measuring point has a weather station set up near the middle of the measuring point. The thermal environment parameters, such as air temperature, relative humidity, air velocity, and black globe temperature (BGT), were recorded at 1.1 m height. All instruments required for actual measurement were calibrated and automatically recorded once every 10 min for 24 h. The measurement range and accuracy of the instruments are shown in Table 2.

Table 2. Instrument measurement range and accuracy.

	Air Temperature	Air Velocity	Humidity	Black Globe Temperature	Surface Temperature	Distance Class
Equipment	NHQXZ602 portable automatic weather station	NHQXZ602 portable automatic weather station	NHQXZ602 portable automatic weather station	Comprehensive temperature and heat index meter 87,786	Electronic pyrometer VC307C	Handheld laser measuring instrument Y40M
Manufacturer	Chen Sen Zhi Yu	Chen Sen Zhi Yu	Chen Sen Zhi Yu	AZ Instrument	VICTOR	YHT
Range	−50–80 °C	0–60 m/s	0–100%RH	0–80 °C	−20–800 °C	0.05–40 m
Accuracy	±0.2 °C	±0.3 m/s	±3%RH	±0.6 °C	±1.5 °C	±1.5 mm
Resolution	0.1 °C	0.1 m/s	1%RH	0.1 °C	0.1 °C	0.001 m

2.3. Questionnaire Data

In addition to traditional and accepted thermal comfort indices, questionnaire-based outdoor thermal comfort surveys were crucial [42]. In this study, a questionnaire survey for users was conducted at the measurement sites while meteorological parameters were collected. Since the main respondents of the questionnaire are anonymous, and the questionnaire does not involve privacy and personal information, about 50% of the invitees accepted the questionnaire. The date and time of the questionnaire survey are shown in Table 3. The questionnaire was completed with the assistance of the students in the research group and divided into four parts, as shown in Table 4. Part 1 is a personal information survey, including gender, age, etc. Part 2 investigates the current dress and metabolic level of the subjects. Part 3 inquires about subjective thermal sensation. Part 4 inquires about different methods of adaptation to the thermal environment. Only those who stayed at the selected site for more than 15 min would be considered for the questionnaire survey. A total of 509 valid questionnaires were collected, including 243 in hot season and 266 in cold season. The age was mainly concentrated between 18 and 30 years, accounting for 95.5%. In the aspect of gender, males accounted for about 58.5% and females about 41.5%. The mean BMI was 21.00, with a standard deviation of 3.22.

Table 3. Date and time of data collection.

Year	Season	Month	Date	Time	Sample Size
2021	hot	September October	23, 24, 25 1, 5, 6	9:00–21:00	243
2022	cold	January	4, 5, 6	9:00–23:00	266

2.4. Calculation of Thermal Comfort

The human comfort sensation involves physiological and psychological factors. According to previous studies, PET is a widely accepted outdoor meteorological index. PET, a comprehensive evaluation index of meteorological parameters based on the Munich Energy-Balance Model for Individuals (MEMI), refers to the physiologically equivalent temperature in any given environment (outdoor or indoor). Its value is equal to the air temperature in a given situation, at which the thermal equilibrium of the human body is maintained and the core and skin temperatures are equal to the temperature under the conditions evaluated [43]. Notably, it assumes the clothing insulation value and activity level, so that the effect of microclimate alone on the thermal state of the body can be evaluated independently of individual behavior [44]. All PET values expressed in degrees Celsius in this paper were calculated using Rayman 1.2. During calculation, air temperature (°C), air velocity (m/s), relative humidity (RH), and mean radiation temperature (T_{mrt}) were used as the main input data.

Table 4. The questionnaire used in this study.

PART1	Time/Location	
	Gender	☐Male ☐Female
	Age	☐<18 ☐18–31 ☐31–45 ☐46–60 ☐>60
	Birthplace	
	Length of stay in Shenzhen	☐Less than 1 month ☐About half a year ☐1–2 years ☐More than 2 years
PART2	Clothing insulation (clo)	Lower Body: ☐T-shirt (0.15) ☐Short-sleeved shirts (0.19) ☐Long-sleeved shirts (0.25) ☐Knitwear (0.28) ☐Hoodie (0.3) ☐Jacket (0.35) ☐Woolen coat (0.45) ☐Down jacket (0.55) Lower Body: ☐Briefs (0.03) ☐Shorts (0.08) ☐Thermal underwear (0.1) ☐Thin outer pants (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 or sandals (0.02) ☐Sneakers (0.1) ☐Leather shoes (0.06)
	Metabolic rate (W/m^2)	☐Sitting (60) ☐Standing (90) ☐Walking (120) ☐Exercising (360)
PART3	Thermal sensation vote (TSV)	☐Cold (−3) ☐Cool (−2) ☐Slightly cool (−1) ☐Neutral (0) ☐Slightly warm (1) ☐Warm (2) ☐Hot (3)
	Thermal comfort vote (TCV)	☐Very comfortable (0) ☐Slightly comfortable (1) ☐Comfortable (2) ☐Slightly uncomfortable (3) ☐Very uncomfortable (4)
	Thermal acceptability vote (TAV)	☐Very unacceptable (−2) ☐Just unacceptable (−1) ☐Just Acceptable (1) ☐Very acceptable (2)
	Thermal preference vote (TPV)	☐Colder (−2) ☐Cooler (−1) ☐Unchanged (0) ☐Warmer (+1) ☐Hotter (+2)
PART4	Adaptive behavior	☐Using umbrellas ☐Wearing a hat ☐Wearing more clothes ☐Wearing less clothes ☐Seeking shade ☐Staying in the sun ☐Having cold drinks ☐Fanning ☐No change ☐Exposure to the sun

Upon the calculation of PET, T_{mrt} (mean radiant temperature) is first calculated, a common parameter used to assess thermal comfort or calculate the radiant heat loss from the human body. T_{mrt} is calculated according to Equation (1):

$$T_{mrt} = \left[\left(T_g + 273 \right)^4 + \left(1.10 \times 10^8 v^{0.6} \right) \left(T_g - T_a \right) / \varepsilon D^{0.4} \right] - 273 \quad (1)$$

where T_{mrt} is the mean radiation temperature (°C), T_g is the black globe temperature (°C), T_a is the air temperature (°C), v is the air velocity (m/s), D is the diameter of the black globe (m) (standard black globe with D = 75 mm is used in this paper), and ε is the absorption rate of the black globe (0.95 in this paper).

2.5. Linear Regression

Linear regression is a regression analysis that uses the least square function or linear regression equation to model the relationship between one or more independent variables and dependent variables. It is the first type of regression analysis that has been strictly studied and widely used in practical applications. This is because a model that depends linearly on its unknown parameters is easier to fit than a model that depends nonlinearly on its unknown parameters, and the statistical characteristics of the resulting estimates are also easier to determine. When linear regression is applied to thermal comfort analysis, the model is easy to understand. At the same time, a broader microclimate state can be fitted.

3. Results

3.1. Outdoor Thermal Environment and Respondent Characteristics

The maximum, minimum, mean, and standard deviation of each parameter of the outdoor thermal environment at each measurement site are shown in Table 5 In terms of air temperature, it was mainly concentrated at 26–33 °C in hot season and 18–24 °C in cold season, and the mean air temperature difference between hot season and cold season was around 10 °C. In terms of relative humidity and air velocity, there was little difference between hot season and cold season. The BGT presented similar characteristics to the air temperature.

Table 5. Thermal environment at each measurement site.

	SITE	Air Temperature (°C)				Relative Humidity (%)				Air Velocity (m/s)				Black Globe Temperature (°C)			
		Max	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**	**Max**	**Min**	**Mean**	**SD**
Hot season	1	33.0	27.8	30.9	1.2	86.7	44.8	68.9	10.0	3.5	0.0	0.4	0.6	32.9	27.8	30.7	1.2
	2	32.9	26.3	30.5	1.4	92.2	46.0	72.2	10.2	4.6	0.0	0.7	0.8	33.2	27.6	30.7	1.3
	3	33.0	26.7	30.5	1.3	93.9	49.6	73.6	9.4	5.7	0.0	0.7	0.9	32.8	26.5	30.1	1.3
	4	32.8	25.8	30.4	1.4	95.8	47.8	74.2	10.5	4.6	0.0	0.5	0.6	32.7	25.4	30.1	1.3
	5	36.2	27.8	31.5	1.8	87.5	41.4	70.2	11.0	4.9	0.0	0.5	0.7	36.2	29.0	32.1	1.4
Cold season	1	23.8	18.5	21.0	1.5	81.4	48.9	68.3	8.2	2.4	0.0	0.2	0.4	23.5	18.6	20.6	1.4
	2	23.3	18.1	20.6	1.6	92.9	51.3	74.9	10.0	5.2	0.0	0.6	0.9	22.9	17.9	20.2	1.5
	3	23.3	18.1	20.6	1.6	96.0	54.5	79.3	9.6	5.3	0.0	0.6	1.0	22.9	18.1	20.2	1.5
	4	23.7	18.8	20.7	1.5	87.2	53.1	73.4	8.5	5.4	0.0	0.6	0.8	23.3	18.4	20.4	1.4
	5	23.3	18.6	20.6	1.2	87.8	50.3	75.4	8.1	2.0	0.0	0.1	0.3	22.7	18.6	20.1	1.1

To understand the influence of microclimatic parameters on outdoor thermal comfort in hot summer and warm winter regions, five meteorological parameters (T_a, T_g, V_a, T_{mrt}, and RH) were analyzed using the correlation analysis method, as shown in Table 6. The results indicated that T_g and T_{mrt} showed a significant positive correlation with PET, and a very close relationship. Ta also showed a significant positive correlation with PET, and a close relationship. Second, V_a showed a significant negative correlation with PET. RH did not show a significant correlation with PET. This may be due to the hot and humid climate of Shenzhen, with high solar radiation intensity and accompanied by low air velocity, which was generally consistent with previous studies [45]. Moreover, among microclimate parameters, T_a and T_g showed a positive correlation with a very close relationship. Moreover, T_g and T_{mrt} showed a positive correlation, with a very close relationship. This is because T_{mrt} was obtained based on the calculation of T_g.

Table 6. Correlation analysis among microclimate parameters.

	PET	T_a	T_g	V_a	T_{mrt}	RH
PET	1.000					
T_a	0.641 **	1.000				
T_g	0.839 **	0.859 **	1.000			
V_a	−0.292 **	0.174 **	0.183 **	1.000		
T_{mrt}	0.713 **	0.467 **	0.796 **	0.138 *	1.000	−0.086
RH	−0.118	−0.481 **	−0.345 **	−0.224 **	−0.086	1.000

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).

3.2. Thermal Sensation and Thermal Comfort

Figure 4 shows the TSV distribution of respondents. It is generally considered that respondents with TSV between −1 and 1 are satisfied with their thermal environment. The percentage of respondents satisfied with their thermal environment in summer was 59.3%. This value increased to 91.7% in cold season, suggesting that these semi-outdoor spaces were more likely to make the respondents feel thermally comfortable in cold season. This may be due to the difference in clothing insulation between cold season and hot season. In hot season, the minimum acceptable amount of clothing given moral constraints still did not allow for thermal sensation in the comfort zone. Yet, the relatively cooler thermal environment in cold season allowed more space for people to adjust their clothing.

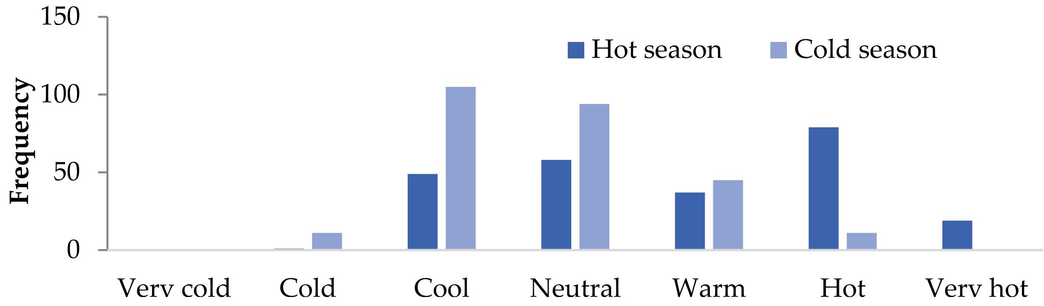

Figure 4. TSV frequency statistics.

The linear regression model of TSV and PET was established, as shown in Figure 5. According to the regression equation, TSV was set to 0, and it could be obtained that the neutral temperature was 28.3 °C in hot season, 23.3 °C in cold season, and 23.8 °C for the whole year. TSV between −0.5 and 0.5 was within the neutral PET range, which was 26.5–30.1 °C in hot season, 17.4–29.1 °C in cold season, and 18.8–28.9 °C for the whole year, as shown in Equations (2)–(4) below:

$$\text{Hot season: TSV} = 0.3103\ \text{PET} - 8.8965\ (R^2 = 0.7693, p = 0.0004) \quad (2)$$

$$\text{Cold season: TSV} = 0.0863\ \text{PET} - 2.0057\ (R^2 = 0.6548, p = 0.0005) \quad (3)$$

$$\text{Whole year: TSV} = 0.0982\ \text{PET} - 2.3661\ (R^2 = 0.5729, p = 0.0001) \quad (4)$$

Figure 6 shows the distribution of TCV frequency. The mean TCV was 1.87 in hot season and 1.62 in cold season, indicating that the overall thermal comfort was higher in cold season than in hot season.

The linear relationship between TCV and PET was established, as shown in Figure 7. It can be observed that the relationship between TCV and PET is close in hot season but not obvious in cold season.

There was a strong correlation between TSV and TCV. Figure 8 shows the correlations between each TSV scale and the mean TCV corresponding to the different seasons. Through binomial curve fitting, the correlations can be expressed by Equations (5)–(7) as follows:

$$\text{Hot season: TCV} = 0.1479\ \text{TSV}\ 2 + 0.2293x + 1.3271\ (R^2 = 0.998) \quad (5)$$

$$\text{Cold season: TCV} = 0.2171\ \text{TSV}\ 2 + 0.068x + 1.4417\ (R^2 = 0.9978) \quad (6)$$

$$\text{Year-round: TCV} = 0.2096\text{TSV2} + 0.0338x + 1.4126\ (R^2 = 0.9906) \quad (7)$$

The most comfortable condition (TSV) was −0.78 in hot season, −0.16 in cold season, and −0.08 for the whole year, indicating that the correlation varied with the season. In the hot season, "slightly cool" was considered as a comfortable thermal sensation, and in cold season, it was "neutral".

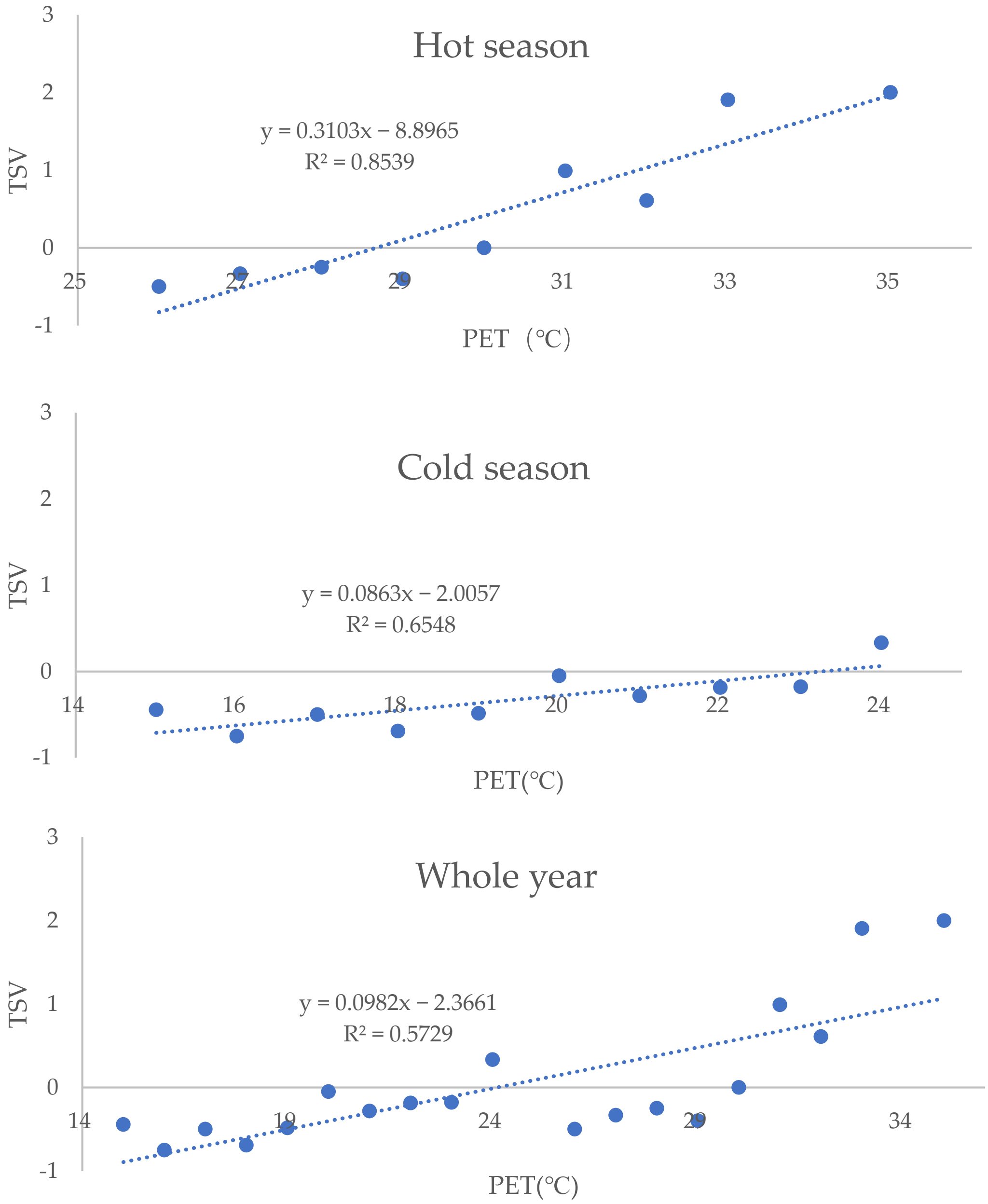

Figure 5. Relationship between TSV and PET.

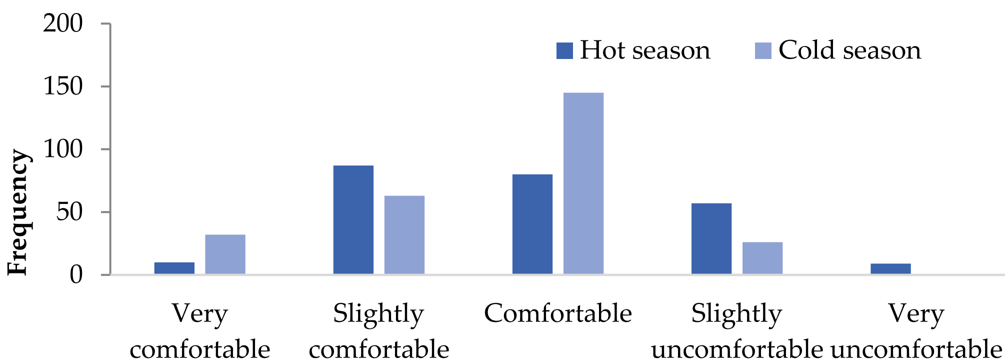

Figure 6. TCV frequency statistics.

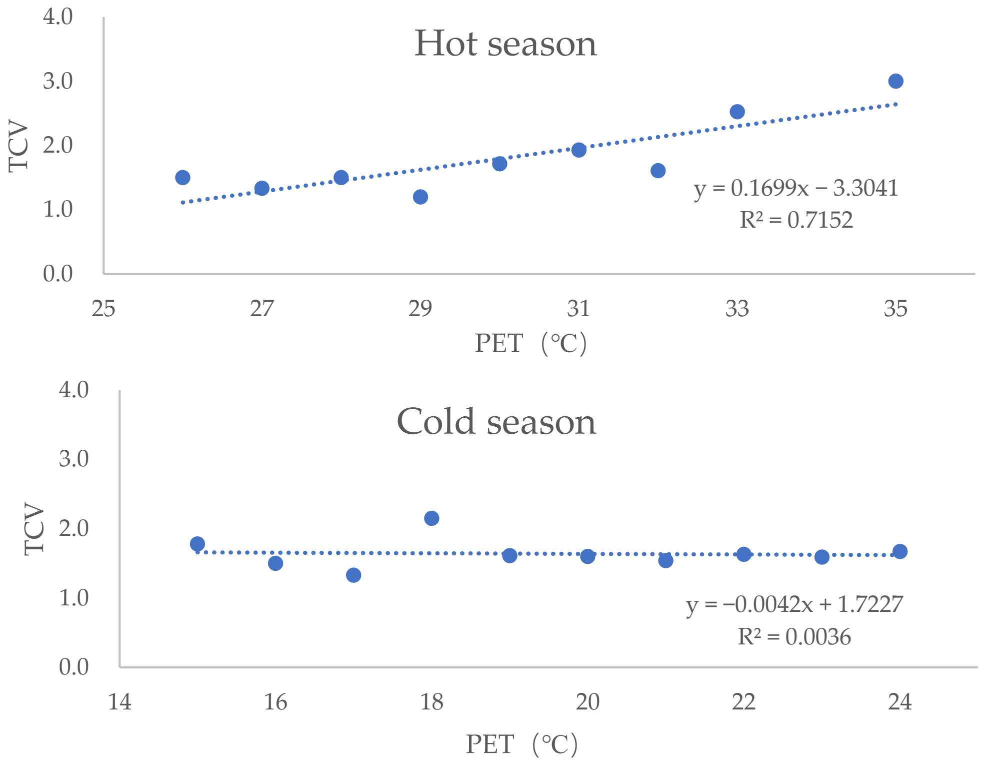

Figure 7. Relationship between TCV and PET.

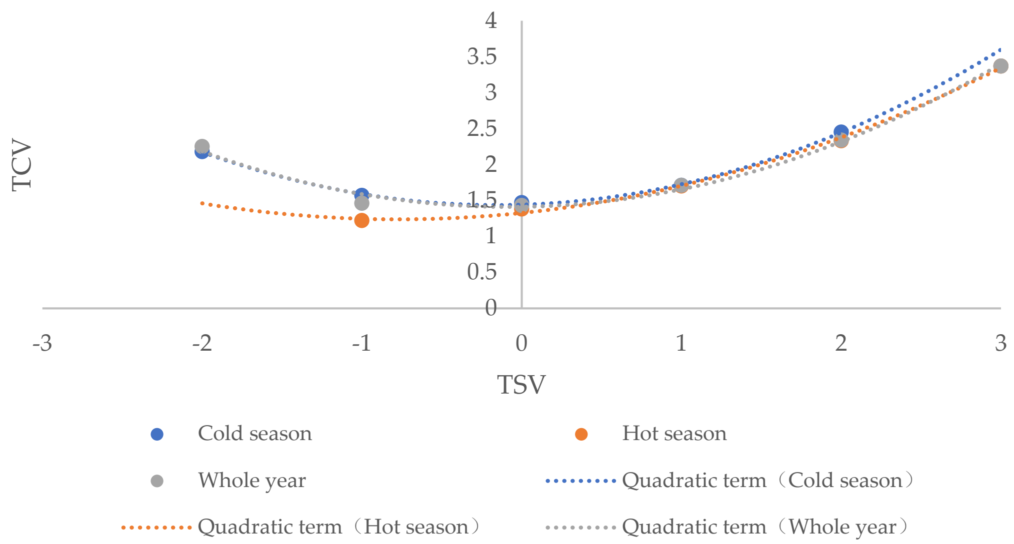

Figure 8. Relationship between TSV and TCV.

3.3. Thermal Acceptability and Thermal Preference

The relationship between the percentage of thermal acceptability (PTA) and PET is shown in Figure 9. ASHRAE 55 recommends that a thermal environment acceptable to 90% of the population is a comfortable thermal environment [46]. According to this criterion and the PTA-PET equation, the PET range acceptable to 90% of the population was 26.2–30.4 °C in hot season, 9.9–19.2 °C in cold season (probably due to clothing), and 17.6–25.3 °C for the whole year.

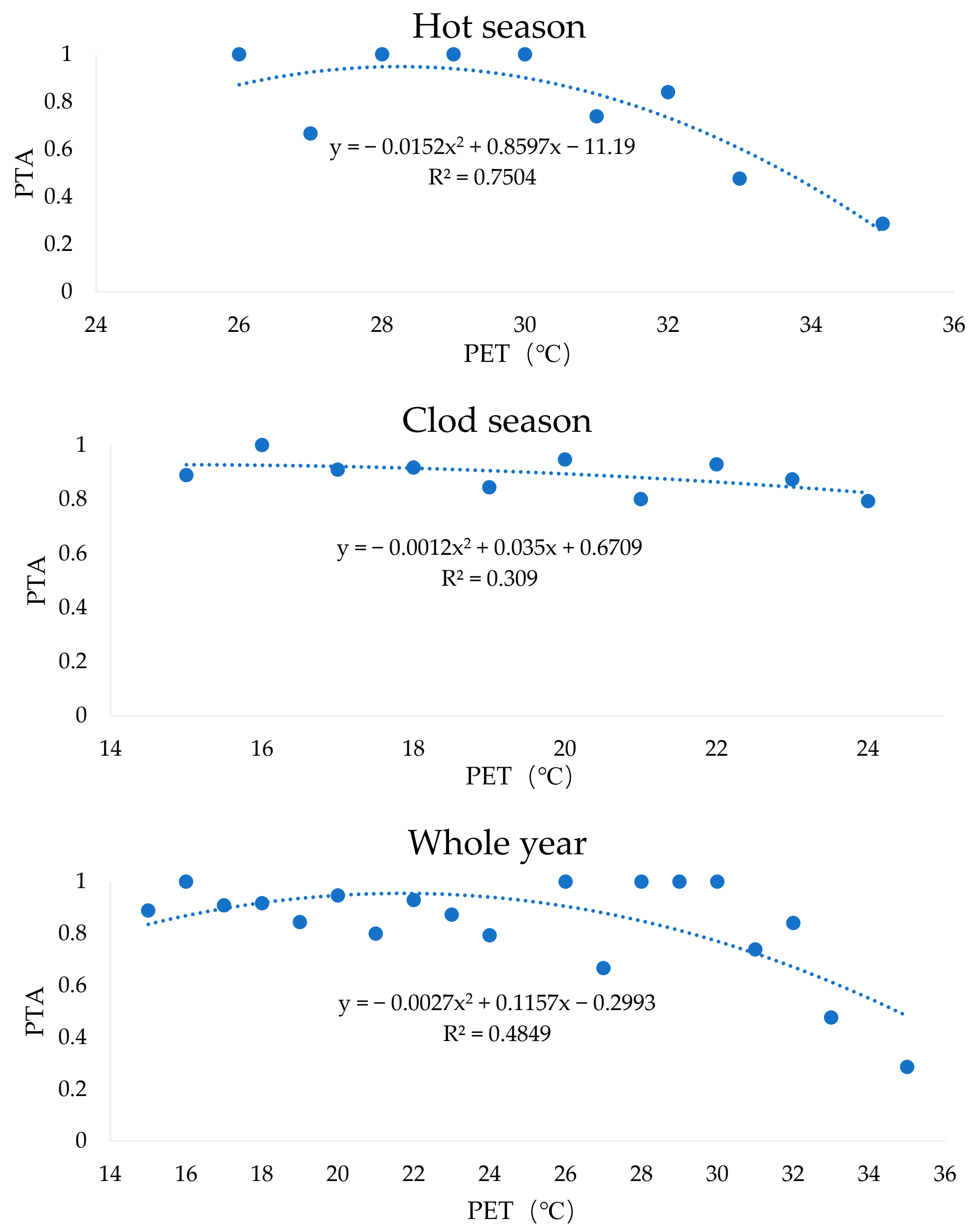

Figure 9. Relationship between PTA and PET.

Terms such as "cold" and "warm" have slightly different meanings depending on the season. In the evaluation scale analyzed, TPV was more suitable than TSV to address seasonal semantic differences [34]. The correlation between TPV and TSV was analyzed, as shown in Table 7. The results indicated that TPV had a highly significant negative correlation with TSV for the whole year. The hotter the thermal sensation, the cooler the thermal preference, and vice versa. Moreover, the correlation between TPV and TSV was higher in cold season than in hot season.

Table 7. Correlation analysis of TPV and TSV.

	Sig. (2-Tailed)	Pearson Correlation	Number of Cases
Hot season	0.001	−0.216 **	243
Cold season	0.000	−0.356 **	266
Year-round	0.000	−0.405 **	509

**. Correlation is significant at the 0.01 level (2-tailed).

In hot season, the mean TPV was −0.73, and the median was −1.00, with the respondents' thermal preferences close to "slightly colder". In cold season, the mean TPV was −0.02, and the median was 0.00, with respondents' thermal preference close to "no change". In hot season, only 7% of the respondents chose "slightly hotter" or "significantly hotter" for thermal preference, and 73% chose "slightly colder" or "significantly colder" for thermal preference. Therefore, it was difficult to identify the preferred temperature in hot season. For the whole year, linear fitting was performed on the relationship between PET and TPV (Figure 10), as shown in Equation (8) below. It can be seen that the preferred temperature for the whole year is 19.0 °C.

$$TPV = -0.0593PET + 1.126 \ (R^2 = 0.5823) \quad (8)$$

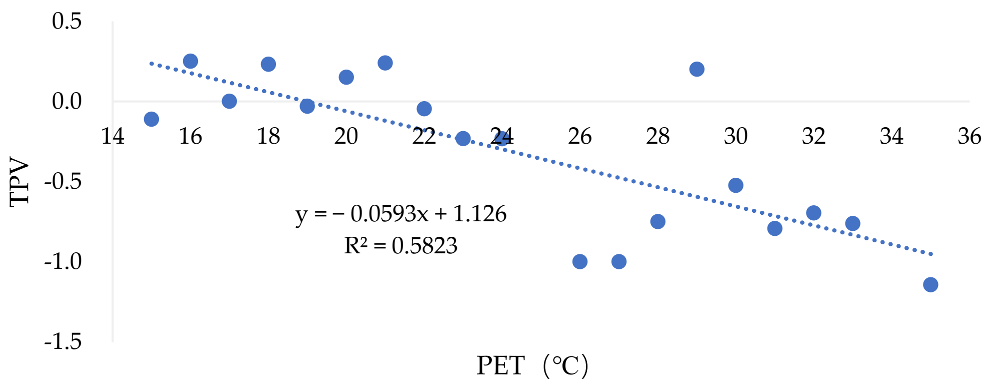

Figure 10. Relationship between TPV and PET.

3.4. Gender Differences

Due to differences in physiological structure, basal metabolic rate (BMR), and multiple environmental and psychological responses, the evaluation and requirements of the thermal environment vary between gender groups. Independent sample *t*-tests were conducted for TSV, TAV, TCV, and TPV to determine whether gender had a significant effect on weather perception. The results are shown in Table 8. Gender showed no significant effect on thermal perception, thermal comfort, thermal acceptability, and thermal preference in the independent seasons of hot season and cold season. However, it had a significant effect on TPV in the year-round analysis, with males expecting colder thermal environments than females.

3.5. Activity and Clothing

The distribution of activity frequency in the overhead spaces is shown in Figure 11. The mean activity level was 85.47 W/m^2 in hot season and 77.14 W/m^2 in cold season, so slightly higher in hot season than in cold season. The mean activity level for the whole year was 81.12 W/m^2. The differences were analyzed with the respondent activity level as the grouping variable (excluding the 350 W/m^2 data for vigorous exercise reported by only one respondent) and TSV, TCV, TAV, and TPV as analysis variables, as shown in Table 9. The results indicated that the level of activity had a significant effect on TSV, but no significant effect on TCV, TAV, and TPV. The greater the activity level, the higher the metabolic rate, and the greater the thermal sensation toward the hot side. The comparison between activity level groups is shown in Table 10, with a significant difference between mild exercise and other groups and no significant difference between other groups.

Table 8. Independent sample *t*-test for gender on weather perception.

Season	Variables	Group	Mean ± sd	t	Sig
Hot season	TSV	Female	1.00 ± 1.42	1.64	0.103
		Male	0.71 ± 1.21		
	TCV	Female	2.00 ± 1.06	1.7	0.09
		Male	1.78 ± 0.85		
	TAV	Female	0.46 ± 1.11	−1.71	0.088
		Male	0.70 ± 0.94		
	TPV	Female	−0.69 ± 0.89	0.67	0.503
		Male	−0.76 ± 0.60		
Cold season	TSV	Female	−0.27 ± 0.91	−0.711	0.478
		Male	−0.19 ± 0.93		
	TCV	Female	1.60 ± 0.87	−0.409	0.683
		Male	1.64 ± 0.79		
	TAV	Female	0.98 ± 0.88	1.015	0.311
		Male	0.88 ± 0.83		
	TPV	Female	−0.07 ± 0.77	1.692	0.092
		Male	−0.09 ± 0.78		
Whole year	TSV	Female	0.18 ± 1.21	−1.5	0.137
		Male	0.35 ± 1.25		
	TCV	Female	1.67 ± 0.91	−1.4	0.161
		Male	1.79 ± 0.87		
	TAV	Female	0.86 ± 0.92	1.78	0.076
		Male	0.71 ± 0.97		
	TPV	Female	−0.26 ± 0.86	2.3	0.022 *
		Male	−0.43 ± 0.81		

*. Correlation is significant at the 0.05 level (2-tailed).

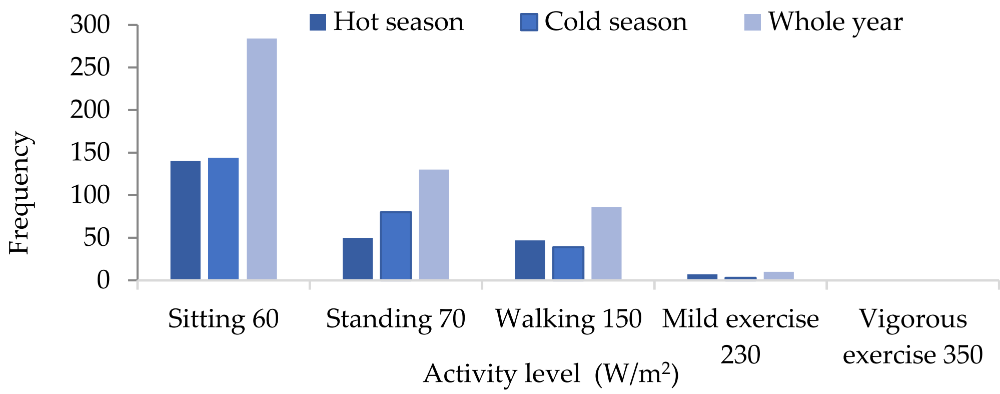

Figure 11. Activity level statistics.

Table 9. Analysis of differences in the effect of activity levels on weather perception.

	60 W/m^2	70 W/m^2	150 W/m^2	230 W/m^2	F	*p*
TSV	0.20 ± 1.26	0.24 ± 1.20	0.43 ± 1.08	1.40 ± 1.51	3.69	0.012 *
TCV	1.70 ± 0.91	1.74 ± 0.82	1.81 ± 0.90	2.10 ± 0.88	0.90	0.440
TAV	0.80 ± 0.98	0.82 ± 0.85	0.65 ± 0.96	0.40 ± 0.97	1.18	0.317
TPV	−0.31 ± 0.89	−0.32 ± 0.78	−0.54 ± 0.67	−0.70 ± 0.82	2.28	0.079

*. Correlation is significant at the 0.05 level (2-tailed).

Table 10. Comparison of activity levels between groups.

Dependent Variable	(I) Activity Level	(J) Activity Level	Difference in Mean (I–J)	Standard Error	Significance
TSV	60	70	−0.04	0.13	0.75
		150	−0.23	0.15	0.12
		230	−1.20 *	0.39	0.00 *
	70	60	0.04	0.13	0.75
		150	−0.19	0.17	0.26
		230	−1.16 *	0.40	0.00 *
	150	60	0.23	0.15	0.12
		70	0.19	0.17	0.26
		230	−0.97 *	0.41	0.02 *
	230	60	1.20 *	0.39	0.00 *
		70	1.16 *	0.40	0.00 *
		150	0.97 *	0.41	0.02 *

*. Difference in mean is significant at the 0.05 level.

The mean clothing insulation in hot season, cold season, and the whole year were 0.48 Clo, 0.71 Clo, and 0.60 Clo, respectively, with standard deviations of 0.11 Clo, 0.18 Clo, and 0.19 Clo. The relationship between clothing insulation and PET was determined using PET as the horizontal coordinate and clothing insulation (Clo) as the vertical coordinate, as shown in Figure 12. The results indicated that clothing insulation did not vary significantly with PET in a single season of hot season and cold season; clothing insulation decreased with the increasing PET throughout the year, consistent with the study by Huang et al. [33].

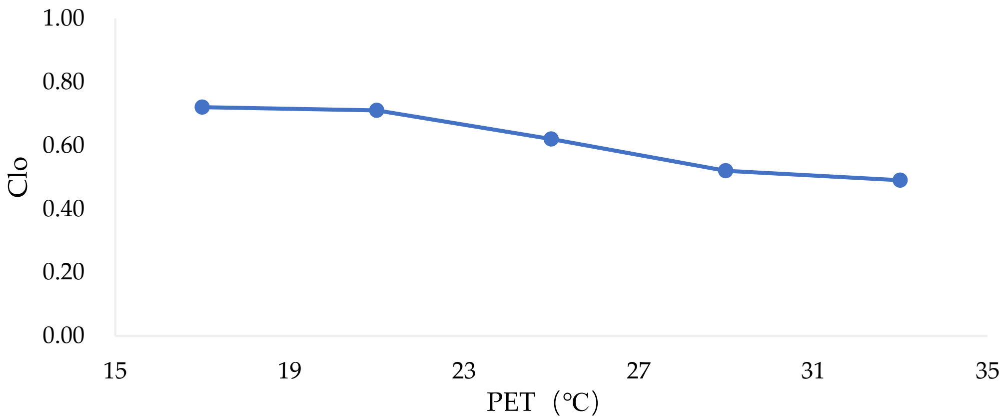

Figure 12. Relationship between clothing insulation and PET.

3.6. Long-Term Thermal History and Short-Term Activity

Thermal history can be divided into long-term and short-term thermal history. The household registration locations of respondents were investigated in the questionnaire and classified into severe cold regions, cold regions, hot summer and cold winter regions, hot summer and warm winter regions, and mild regions according to the Thermal Design Code for Civil Buildings GB 50176-2016 [47]. Shenzhen falls into the hot summer and warm winter region. Among the valid questionnaires collected, the percentage of respondents living in this climate zone for a long time was 69%, and the total percentage of respondents in the remaining four types of climate zones was 31%. Difference analysis was performed on the respondents using the household registration regions as the grouping variable to see whether long-term residence had a significant effect on TSV, TCV, TAV, and TPV, as shown in Table 11. Results indicated that long-term residence had no significant effect on people's TSV and TPV, but had a significant effect on TCV and TAV. Post hoc tests indicated that for TCV, there was a significant difference between cold regions and hot summer and warm winter regions, and a significant difference between mild regions and hot summer and cold winter regions. Respondents from cold regions and mild regions had higher thermal acceptability. For TAV, there was a significant difference between hot summer and cold winter regions and hot summer and warm winter regions. Respondents from hot summer and cold winter regions had higher thermal acceptability than those from hot summer and warm winter regions during the survey.

Table 11. Difference analysis of long-term residence and weather perception.

	Severely Cold Regions	Cold Regions	Hot Summer and Cold Winter Regions	Hot Summer and Warm Winter Regions	Mild Regions	F	*p*
TSV	0.31 ± 1.18	0.34 ± 1.09	−0.03 ± 1.07	0.36 ± 1.29	−0.11 ± 0.93	2.165	0.072
TCV	1.62 ± 0.96	1.37 ± 0.86	1.68 ± 0.85	1.82 ± 0.89	1.11 ± 0.78	3.845	0.004 **
TAV	1.00 ± 0.71	0.98 ± 0.85	0.97 ± 0.78	0.67 ± 1.00	1.22 ± 0.44	3.215	0.013 *
TPV	−0.54 ± 0.66	−0.12 ± 0.87	−0.21 ± 0.82	−0.42 ± 0.83	−0.44 ± 1.01	2.271	0.061

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).

Meanwhile, the activity status of respondents in the first 15 min or so was investigated in the questionnaire and classified into four groups based on the respondent reports (walking, sitting, eating, and others) to see whether short-term thermal history had a significant effect on TSV, TCV, TAV, and TPV. One-way ANOVA difference analysis was performed, as shown in Table 12. The results indicated that short-term thermal history had a significant effect on TSV, but not on TCV, TAV, and TPV. That is, short-term thermal history in hot season had a relatively significant effect on people's thermal sensation, and respondents who had performed certain activities in the short term felt that the current environment was a little bit hotter.

Table 12. Difference analysis of short-term activity and weather perception.

	Walking	Sitting	Eating	Others	F	*p*
TSV	0.88 ± 1.25	0.63 ± 1.34	0.91 ± 1.14	1.63 ± 1.31	2.94	0.03 *
TCV	1.91 ± 0.96	1.80 ± 0.94	1.91 ± 0.83	2.00 ± 0.97	0.39	0.76
TAV	0.62 ± 1.06	0.57 ± 1.02	0.91 ± 0.70	0.50 ± 0.89	0.42	0.74
TPV	−0.68 ± 0.76	−0.80 ± 0.73	−0.55 ± 0.82	−0.81 ± 0.40	0.74	0.53

*. Correlation is significant at the 0.05 level (2-tailed).

3.7. Adaptive Behavior

Nikolopoulou and Steemers pointed out that the concept of adaptation could be used to understand thermal comfort in outdoor and semi-outdoor environments effectively [9]. Brager and de Dear considered that thermal adaptation included behavioral, physiological, and psychological aspects [28]. Regarding short-term behavioral adaptation, respondents were asked about the measures they tended to take to regulate thermal comfort for the current thermal environment. The descriptive statistics are shown in Table 13, and the frequency distribution is shown in Figure 13. In hot season, the response rate of "no change" was 7.30%. In cold season, this value increased to 20.39%, indicating that the thermal environment in the overhead spaces was more comfortable in cold season than in hot season. In hot season, the highest response rates were "seeking shade" (28.20%) and "having cold drinks" (24.10%), and the response rates of these two options in cold season were still not low (17.94% and 15.72% respectively), indicating that there were still users who felt relatively hot in Shenzhen in cold season. The response rate of adaptive behaviors to adjust thermal comfort was the highest in both hot season and cold season. The comparison of cold season and hot season options of "using a sun umbrella" and "exposure to the sun" suggested that respondents in cold season were more comfortable being exposed to the sun than in hot season. In both hot season and cold season, there were users who chose "wearing a hat", probably due to the function of hats, which could serve as sunshade in hot season and keep warm in cold season. In terms of clothing, respondents in both cold season and hot season chose "wearing less clothes", but almost all respondents in cold season chose "wearing more clothes". Moreover, the frequency of adaptive behaviors being selected (excluding the "no change" option) was 199.10% in hot season and 121.81% in the cold season. This might be due to the fact that respondents were more eager to adapt to their thermal environment in hot season, which was also confirmed by the selection rate of "no change" in different seasons as mentioned above.

Table 13. Descriptive statistics of adaptive behavior.

	Measures	Response		
		Number of Cases	**Percentage**	**Percentage of Cases**
Hot season	Use umbrella	66	12.70%	27.40%
	Wearing a hat	19	3.70%	7.90%
	Wearing less clothes	49	9.50%	20.30%
	Having cold drinks	125	24.10%	51.90%
	Seeking shade	146	28.20%	60.60%
	Fanning	71	13.70%	29.50%
	No change	38	7.30%	15.80%
	Exposure to the sun	1	0.20%	0.40%
	Wearing more clothes	3	0.60%	1.20%
	Total	518	100.00%	214.90%
Cold season	Use umbrella	26	6.39%	9.77%
	Wearing a hat	22	5.41%	8.27%
	Wearing less clothes	48	11.79%	18.05%
	Having cold drinks	64	15.72%	24.06%
	Seeking shade	73	17.94%	27.44%
	Fanning	11	2.70%	4.14%
	No change	83	20.39%	31.20%
	Exposure to the sun	42	10.32%	15.79%
	Wearing more clothes	38	9.34%	14.29%
	Total	407	100.00%	153.01%

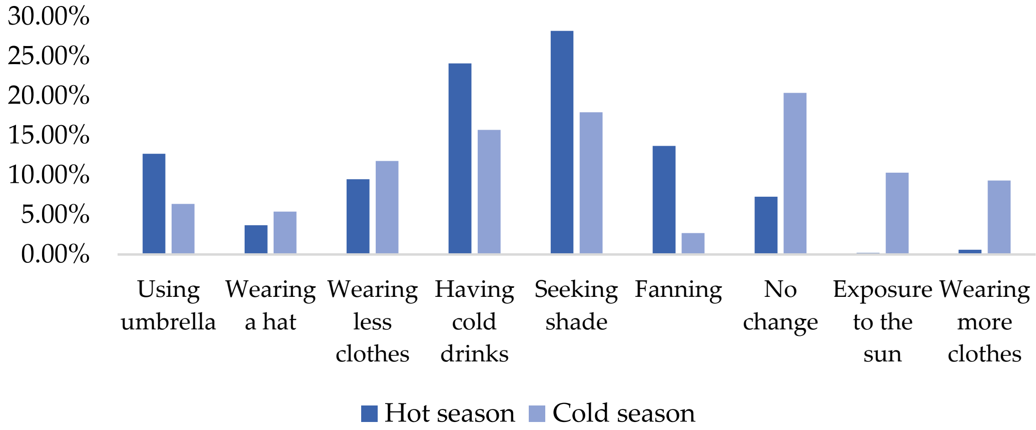

Figure 13. Adaptive behavior statistics.

To understand the gender differences in the selection of adaptive behaviors, Figure 14 was created. Different genders showed a generally consistent trend in the options for each adaptive behavior. For individual options, if the ratio of two genders being greater than two was considered a significant difference, then female respondents were significantly more likely to respond with "wearing more clothes" than male respondents in cold season. Only one female respondent reported "exposure to the sun" in hot season, which may be a coincidence and will not be further discussed.

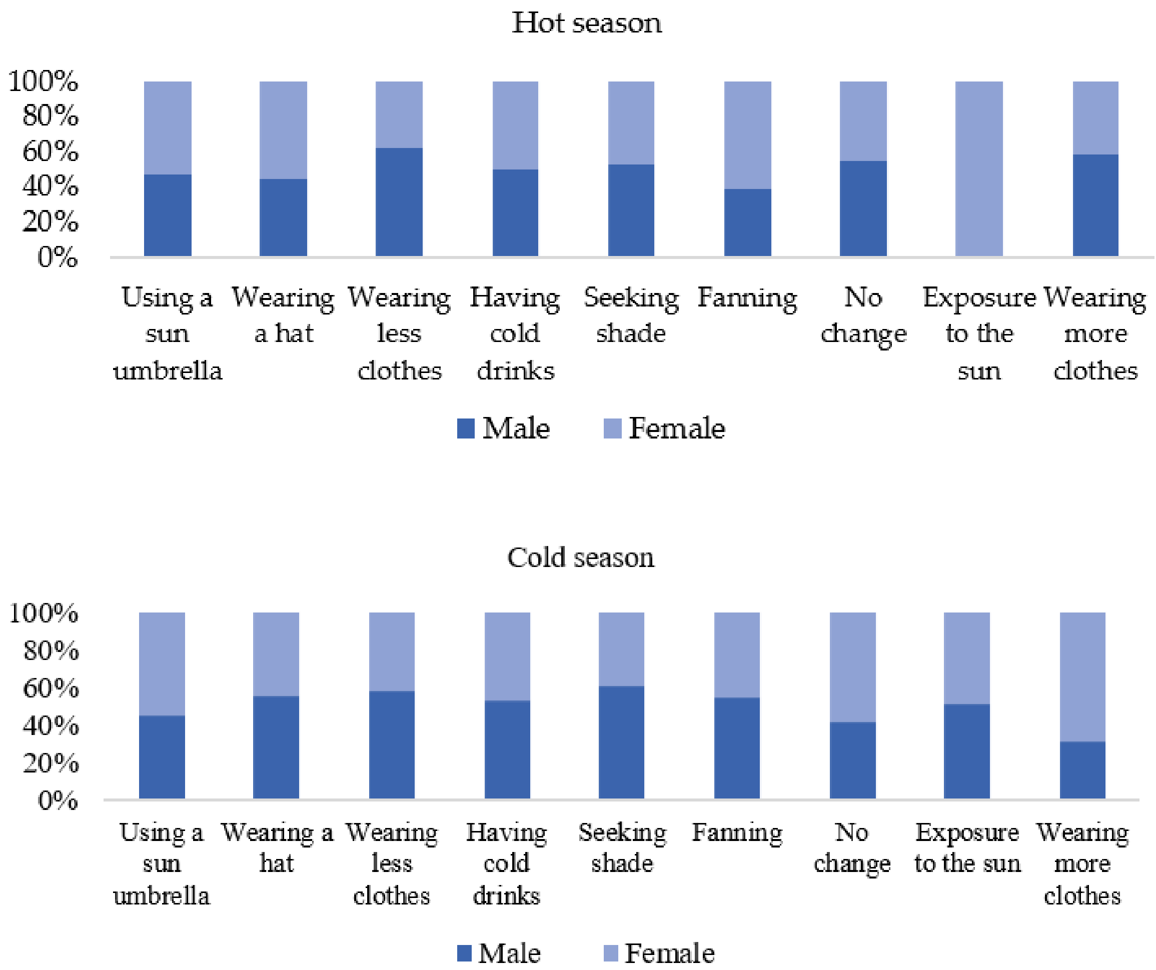

Figure 14. Selection rate of male and female adaptive behaviors in different seasons.

4. Discussion

4.1. Spatial Comparison

To understand the thermal characteristics of thermal environments in different spaces, studies with PET as a thermal comfort index in hot summer and warm winter regions of China were selected for comparison, as shown in Table 14. Green space and waterfront could effectively reduce PET in hot season. According to the study by Lin and Matzarakis for PET classification [48], Shenzhen fell into the subtropical region with a neutral range of 26–30 °C, and cool and warm ranges of 22–26 °C and 30–34 °C, respectively. The thermally acceptable range of PET was a set of cool, neutral, and warm intervals, i.e., 22–34 °C. In the present study, PET was mainly concentrated in 29–34 °C in hot season and 18–24 °C in cold season. Given the short cold season and long hot season in Shenzhen, the thermal comfort of overhead spaces in Shenzhen was essentially in an acceptable range throughout the year, indicating that the overhead spaces in Shenzhen could provide a comfortable thermal environment for users almost all year round. In the future design of overhead spaces, more green space and waterfront landscape elements should be incorporated to further optimize the thermal environment of overhead spaces.

Table 14. Mean hot season and cold season PET for different spaces in hot summer and warm winter regions.

Cities	Space Type	Mean PET in Hot Season (°C)	Mean PET in Cold Season (°C)	Ref.
Guangzhou	Urban green space	30.7–34.2	11.3–12.9	[49]
Shenzhen	Multiple types	29–39	/	[48]
Hong Kong	Open square	26–29	19–21	[44]
Taiwan	Waterfront space	21.6–23.9	12.1–14.7	[50]
Guangzhou/Foshan	Garden courtyard	30–35	/	[51]
Dongguan	Garden courtyard	33–40	/	[51]
Shenzhen	Overhead space	29–34	18–24	-

4.2. Seasonal Differences in Thermal Sensation

According to the hypothetical classification by Lai et al. [52], statistics on the relationship between TSV and PET in different regions are shown in Table 15. The statistics on neutral PET and PET/TSV in different regions are shown in Table 16.

Table 15. Relationship between TSV and PET for Shenzhen, Tianjin residents, Europeans, and Taiwanese.

Thermal Sensation	PET in Shenzhen (°C)	PET in Tianjin (°C)	PET in Europe (°C)	PET in Taiwan (°C)
Very Cold	<−17 [a]	<-16	<4	<14
Cold	−17 to −6 [a]	−16 to −11	4–8	14–18
Cool	−6 to 6 [a]	−11 to −6	8–13	18–22
Slightly cool	6–17	−6 to 11	13–18	22–26
Neutral	17–30	11–24	18–23	26–30
Slightly warm	30–34	24–31	23–29	30–34
Warm	34–37	31–36	29–35	34–38
Hot	37–40 [a]	36–46	35–41	38–42
Very Hot	>40 [a]	>46	>41	>42

[a] Sensation obtained by linear regression.

Table 16. Neutral PET and PET/TSV for Tianjin, Taichung, Hong Kong, Rome, Cairo, Damascus, Sydney and Shenzhen.

City	Location	Neutral PET (°C)		PET/TSV (°C)		Ref.
		Cold Season	Hot Season	Cold Season	Hot Season	
Tianjin, China	38.3° N, 116.4° E	9.2	15.6	5.3	10	[52]
Taichung, Taiwan	24.1° N, 120.7° E	23.7	25.6	5	8.4	[53]
Hong Kong, China	22.3° N, 114.2° E	21	25	8.4	7.3	[44]
Rome, Italy	41.5° N, 12.3° E	24.9	26.9	8.5	5.9	[54]
Cairo, Egypt	31.0° N, 31.3° E	26.5	27.4	-	-	[55]
Damascus, Syria	33.6° N, 36.3° E	24.2	15.7	8.8	16.7	[56]
Sydney, Australia	33.9° S, 151.2° E	28.8	22.9	-	-	[17]
Shenzhen, China	22.5° N, 113.9° E	23.3	28.3	11.1	3.6	-

In this study, neutral PET was 28.3 °C in hot season and 23.3 °C in cold season. Neutral PET increased as the season shifted from cold to hot, consistent with the results for Tianjin [52], Taichung [53], Hong Kong [44], Rome [54], and Cairo [55]. The studies in these regions concluded that people's thermal sensation changed with the season and that inhabitants' tolerance to the thermal environment in hot season increased, so neutral PET increased. However, studies in Damascus [56] and Sydney [17] had different results: neutral PET decreased as the season shifted from cold to hot. Latter studies suggested that differences in thermal sensation preferences across seasons could be attributed to the concept of "synesthesia" which indicates that warm sensations were perceived as more comfortable than cool ones during the cold season, and vice versa during the hot season.

Different climatic conditions, ethnicity, and cultural practices were all possible factors contributing to the differences in neutral temperature in various regions.

In addition, the slopes of PET corresponding to TSV in each season in this study were 0.28 in hot season, 0.09 in cold season, and 0.10 for the whole year, respectively. The TSV/PET was 3.6 °C in hot season, 11.1 °C in cold season, and 10.0 °C for the whole year. This suggested that the TSV of respondents was more sensitive in hot season, insensitive in cold season, and in-between throughout the year, indicating that this experience changed their perception of the thermal environment. The same phenomenon was observed in Hong Kong [44] and Rome [54]. The cold season PET/TSV was 8.4 and 8.5, and hot season PET/TSV was 7.3 and 5.9, respectively. Other studies such as Tianjin [52], Taichung [53], and Damascus [56] reported different phenomena (Table 16). PET/TSV in cold season was 5.3, 5, and 8.8, and PET/TSV in hot season was 10, 8.4, and 16.7, respectively. Thermal sensitivity was a complex issue, involving multiple factors, such as local climate, physical (activities and clothing), and psychological (experience and expectations) aspects.

4.3. Thermal Comfort and Comfort PET Range

In hot season, a slightly cool thermal sensation (TSV = −0.78) was considered more comfortable than a neutral thermal sensation (TSV = 0). Similarly, in cold season, the most comfortable thermal sensation is not neutral (TSV = 0) strictly, but TSV = −0.16. This suggested that the optimal thermal sensation would change with the season, and neutral thermal sensation was not the situation where the respondents felt most comfortable. The neutral temperatures were 28.3 °C and 23.3 °C in hot season and cold season, respectively, while the optimal temperatures were 25.5 °C and 21.4 °C in hot season and cold season, respectively, which were 2.8 °C and 1.9 °C lower than the neutral PET. The seasonal thermal preferences found in this study differed from those by Lai [52] and Li [57]. Lai found the most comfortable TSV to be 0.86 in the cold season, 0.08 in the transition season, and −1.07 in the hot season. Li found the most comfortable TSV to be 1 in the cold season, 0.2 in the transition season, and −0.3 in the hot season. This may be due to the geographical locations and climatic conditions of Shenzhen and Tianjin, where the temperature conditions in hot season had no significant difference, but the climate of Shenzhen in cold season may be more similar to that of Tianjin in the transition season (close to TSV = 0).

The acceptable PET range for 90% of the population in this study was 26.2–30.4 °C in hot season, 9.9–19.2 °C in cold season, and 17.6–25.3 °C for the whole year. The mean monthly temperature in Shenzhen was 15.1–29.0 °C PET. Lin found in a study of the humid subtropical region in Taiwan [53] (mean monthly temperature is 13–29 °C) that the acceptable PET range for 90% of the population was 21.3–28.5 °C PET. The acceptable PET range for 90% of the population in Europe [58] (mean monthly temperature is 2–20 °C) was 18–23 °C. The acceptable PET range for 90% of the population in Guangzhou [57] (mean monthly temperature is 2–20 °C) was 18.1–31.1 °C. The results of Shenzhen were closer to those of Guangzhou and Taiwan, which were significantly wider than those of Europe. This may be due to the fact that Shenzhen, Guangzhou, and Taiwan are classified as hot summer and warm winter regions, which differ significantly from the European climate.

4.4. Gender Differences

The results of the *t*-test for TSV and TCV by gender showed that gender may not be related to TSV and TCV. This result supported Huang's survey in Mianyang [33], different from the results obtained by Donnini [59] and Tung et al. [60]. Donnini investigated the neutral temperature of different genders in southern Quebec and found that the neutral temperature of females was 0.3 °C higher than that of males. Tung et al. found in their study in Taiwan that the neutral temperature of females was 0.9 °C lower than that of males. Hence, the effect of gender on thermal sensation may be influenced by regional differences and ethnicity. The *t*-test results of TPV by gender indicated that gender differences had a significant effect on TPV, with males preferring colder thermal environments than females.

4.5. Adaptive Behaviors

The regulation of thermal comfort through clothing is the most frequently considered and fundamental. Wearing more or less clothing is the most direct way for people to regulate thermal comfort, which has been verified by many studies [61]. For the whole year, clothing insulation (Clo) decreased gradually with the increasing PET, and vice versa. However, this was not obvious within a single season. Similarly, in terms of activity, adaptive behaviors with seasonal changes were also demonstrated. People were more active in hot season than in cold season. This suggested that people tended to conduct non-indoor activities in hot season, while preferring indoor activities or reducing activity levels when the temperature dropped in cold season, consistent with the study conducted by Huang et al. [33] in Mianyang.

5. Conclusions

In this paper, a field study was conducted on the thermal comfort and adaptive behaviors in the overhead spaces of SZU in different seasons, using a combination of actual measurement and questionnaires. It has enriched the literature on thermal comfort of semi-open spaces in hot summer and warm winter regions and expanded the research theory concerning the planning and design of campus activity spaces based on climate adaptation. The results of the study may be useful for building planning practices in hot summer and warm winter regions and provide partial references for campus planning and design. The main conclusions of this study are as follows.

In the aspect of thermal sensation, overhead spaces in Shenzhen can provide users with a comfortable thermal environment nearly all year round. The mean PET was 31.2 °C in hot season, 20.9 °C in cold season, and 25.8 °C for the whole year. The neutral temperature was 27.7 °C in hot season, 23.3 °C in cold season, and 23.2 °C for the whole year. The preferred temperature for the whole year was 19.0 °C. In hot season, people felt more comfortable with a lower PET and 90% of the people had an acceptable PET range of 26.2–30.4 °C. In cold season, people's thermal sensation did not change significantly with PET and the acceptable PET range for 90% of the population was 9.9–19.2 °C. Throughout the year, the acceptable PET range for 90% of the population was 17.6–25.3 °C. As the season shifted from cold to hot, neutral PET increased. In both hot season and cold season, slightly cool (TSV = −0.78) and neutral (TSV = −0.16) thermal sensations were considered more comfortable than neutral ones (TSV = 0).

In the aspect of possible influences on thermal comfort, gender was not related to TSV, TCV, TAV, but related to TPV, with males expecting a colder thermal environment than women. In hot season, the mean activity level of respondents was 85.47 W/m^2, and the mean clothing insulation was 0.48 Clo. In cold season, the mean activity level of respondents was 76.87 W/m^2, and the mean clothing insulation was 0.71 Clo. The relationship between activity and PET was not significant within independent seasons of hot season or cold season. Similarly, clothing insulation values did not vary significantly with PET within independent seasons. Throughout the year, clothing insulation decreased slightly with the increasing PET. Long-term residences had no significant effect on people's TSV and TPV, but a significant effect on TCV and TAV. Respondents from cold and mild regions had higher TCV, while those from hot summer and cold winter regions had higher TAV to the environment than those from hot summer and warm winter regions.

Regarding the aspect of adaptive behaviors, the response rates of "seeking shade" and "having cold drinks" were significantly higher than the other options, indicating that people's adaptive behaviors could be performed from changing both the physical environment and their own metabolism. The desire to adjust thermal comfort was stronger in hot season than in the cold season.

Based on the above, some observations are as follows: (1) The optimum TSVs in the hot season and the cold season are −0.78 and −0.16 respectively. Considering the long hot season and the short cold season in Shenzhen, greater consideration should be given to measures to reduce PET in the hot season when designing overhead spaces. The hot season is more sensitive to sunlight, and the addition of shading facilities can increase the usable area of the overhead spaces in the hot season. (2) People in different regions have significant differences in TCV and TAV. In a university campus with diverse populations, it is necessary to fully understand the thermal comfort threshold of people from various regions and to capture the diversity in the design of overhead spaces, so as to provide a comfortable experience for a wider range of people. (3) The cold season in Shenzhen is different from most areas in China, and most users still do not feel cold. Therefore, when designing the overhead spaces in Shenzhen, it is unnecessary to consider too many thermal protection measures, such as cold season wind protection. (4) PET is significantly higher than other measuring points near the measuring points of HVAC and other equipment. The location of HVAC and other heat rejection equipment should be reasonably planned in the overhead spaces of the buildings to reduce their negative impact on the thermal comfort of users.

There are also limitations in this study: (1) This study only collected data in late September/early October and early January due to the academic calendar, missing out on the most extreme periods for the climate in Shenzhen, such as August. (2) The samples of the questionnaire survey focused on the student group aged 18–30 years, and populations such as faculty members were missing. To gain a comprehensive understanding of the thermal comfort conditions in semi-open spaces in hot summer and cold winter regions, it is necessary to extend the study to more seasons and cover more campus users in the study population. Although statistical analysis can be conducted based on the sample size of this study, a larger sample size would allow for higher-order statistical analysis and provide more convincing results.

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Abbreviations

Abbreviation	Full Name
T_a	Air temperature (°C)
T_g	Black globe temperature (°C)
T_{mrt}	Mean radiant temperature(°C)
V_a	Air velocity (m/s)
RH	Relative humidity (%)
BMI	Body mass index
PET	Physiologically equivalent temperature (°C)
PTA	Percentage of thermal acceptability (%)
TAV	Thermal acceptability vote
TCV	Thermal comfort vote
TPV	Thermal preference vote
TSV	Thermal sensation vote

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